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# Model Basis for the Navigation Aid Analysis Tool

**FINAL REPORT**
**OCTOBER 1999**



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# N O T I C E

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16. Abstract (MAXIMUM 200 WORDS)

This report describes the development of models used in the Navigation Aid Analysis Tool (NAAT), a self-contained software product that computes the probability of being in a given system state, most commonly, the incident state, for a user-constructed scenario of surface marine navigation in harbor entrance and approach navigation areas. The report describes error models of visual navigation systems, constructed so as to place them on an equal footing with other commonly used radionavigation systems. The report also traces the methods used to create a dynamic Markov state space model, necessary for determining incident rates for arbitrary input of user navigation systems, navigation areas, and vessel characteristics. For a given scenario, the computed incident rate may be compared to the target level of safety to determine if navigation requirements are met.

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# Executive Summary

The USCG Research and Development Center is conducting the Aid Mix project to develop system analysis tools for the USCG Office of Aids to Navigation. A significant part of this research is to determine the performance of various combinations of navigational aids. In order to quantify the navigational performance in terms of safety, we have developed the Navigation Aid Analysis Tool (NAAT). The objective of this report is to describe the theoretical structure and models underlying NAAT. NAAT is a software package, written and executed in MATLAB™, that calculates the probability of an incident (vessel grounding or collision with the edge of the channel) for a user-specified navigation scenario. The scenario includes data on the vessel characteristics, the navigation area through which the vessel is transiting, the navigation equipment on board the vessel and/or supporting infrastructure in the navigation area, and certain environmental conditions. The incident probability may be compared with a target level of safety (TLS) based on historical casualty rates or any other figure selected by the NAAT operator.

In addition to vessel size parameters and navigation area geography, NAAT input incorporates several navigational aids. Visual aids, Differential GPS, Loran, GPS, inertial navigation systems are included and the users can specify the characteristics of an additional aid to test any proposed systems. The user can edit the performance, selection and priority of any combination of these aids. When electronic aids are selected, the use of an electronic chart display system is automatically included. The user must assign relevant performance data to each navigational aid system. Performance data includes accuracy, mean time to failure and mean time to repair. The user can use the various navigation systems' actual values for these terms or potentially change them to investigate the effects of system improvements or operational doctrine changes. For example, the user could examine the effect of removal of GPS selective availability (improvement in GPS accuracy) on incident rate.

A key aspect of this work was the development of a visual navigation state to include short-range aids in a systematic fashion with radio-aids. Calculations for this

state are based on two incident models: an empirical/statistical model invoked when any aids are visible, and a first-principles dead reckoning model for use in zero-visibility conditions. Another important development that makes this tool useful for studying arbitrary navigation areas and systems is the method devised to dynamically configure the Markov state space model for navigation incident probability. This means that the NAAT operator can construct and test his own scenarios rather than the fixed scenarios considered in earlier work. For the convenience of the NAAT operator, a vessel catalog has been compiled and channel configurations have been constructed for the Tampa Bay and St. Mary's River navigation areas.

To increase its applicability and realism, the formerly one-dimensional model has been improved to include a two-dimensional turn sub-model based on smoothly continuous trajectory transitions between straight transit segments. The vessel control procedure assumed for turns is similar to the straight channel sections, i.e., the vessel is steered to the desired trackline/centerline, except that for turns, the trackline is assumed to be the arc of a circle with user-selectable length and pre-defined radius of curvature.

In conclusion, NAAT can be used to compare the relative safety margins for various combinations of primary/secondary navigation systems, different vessel types, and alternative navigation areas. NAAT can also be used to determine the relative safety of different portions of the navigation area. Another important application of NAAT is to examine the interrelationships between the TLS and critical navigation system parameters. This technique, referred to as sensitivity analysis, can be used to identify crucial parameters for any system and the effect of these parameters on system performance. NAAT is an important tool in analyzing the mix of aids-to-navigation provided by the Coast Guard. It forms the basis of the navigation performance analysis for the overall Aid Mix methodology. The next step in applying NAAT to the Aid Mix problem is to perform an independent verification and validation (IV&V). An IV&V will ensure that the NAAT implementation is as described and that NAAT provides valid information when used.

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# 1. Introduction

This report is a compilation of the model and algorithm development that serves as the basis for the Navigation Aid Analysis Tool (NAAT). It incorporates prior documentation (Morris and McGaffigan, 1999a,b), as modified, of the models used in NAAT, in addition to some new material.

Development of the models divides roughly into two principal tasks:

1. Visual navigation analysis
2. Extension of earlier work on radionavigation system state space analysis

Task 1 includes definition of visual navigation states, development of incident probability models for the visual states, and specification of parameters that define the visual states. Task 2 includes modifications of the original algorithms/code to permit arbitrary input of navigation system, use priority, navigation area, and vessel parameters. Since the choice of navigation system can include visual navigation, the two tasks are clearly related. Using this structure, we will describe the elements of the models and how they were developed.

This chapter contains background information on previous supporting work, as well as the scope and objectives of the current effort. Chapter 2 outlines the basis for the visual navigation incident error model (Section 2.1/Task 1) and the dynamic specification of the Markov chain (Section 2.2/Task 2). Chapter 3 presents the detailed parameter definitions and incident rate models for the visual navigation state addressed by Task 1. The specification of the navigation area and user vessel is described in Chapter 4. The technique employed for calculating vessel incident rates in turns is explained in Chapter 5. The final chapter presents the summary of the work, principal conclusions, and recommendations for needed additional work.

## 1.1 Background

In two previous efforts sponsored by the Coast Guard Navigation Center (Creamer, 1997 and Morris, 1999), a methodology was developed to assist in evaluating the navigational performance of the U.S. Coast Guard Differential GPS (DGPS) service for larger commercial vessels operating in a variety of U.S. waterways under low/zero visibility conditions. Navigational performance was evaluated in terms of the probability of an incident (in this case, a grounding) using a Markov Chain technique, in which the status of navigation service is identified by a series of states. The performance was calculated for vessels using DGPS and several alternative backup systems; the resulting incident rates were compared to a target level of safety (TLS) derived from an accident database (Creamer, *et al*, 1997).

Using this methodology, it was found that the current level of performance of DGPS service and conventional receivers was sufficient to satisfy the TLS for average and "navigationally benign" waterways in the U.S, assuming marine radar as a backup to DGPS. Under these same assumptions, however, calculations showed the TLS could not be met for the more challenging waterways in low/zero visibility conditions.

The results suggested that failure to achieve the TLS is most often due to the lack of position accuracy of the on-board navigation systems serving as backup to DGPS. To further explore this general observation, scenarios were constructed for vessels transiting the navigationally challenging areas in Tampa Bay and the St. Mary's River. These scenarios involve the following three DGPS backup system configurations:

- Loran-C
- INS/IMU
- GPS using satellites not corrupted with selective availability (SA).

A key assumption is that all backup systems are continuously calibrated by DGPS whenever both systems are available. When DGPS fails, the backup system evolves from

an accuracy state characteristic of DGPS to that of the backup system in its stand-alone mode.

Simulations of these scenarios involving the three primary/secondary navigation systems and the two navigationally challenging navigation areas show that the DGPS/Loran-C configuration satisfies the TLS for nearly every scenario due to Loran-C's slow error growth, its high reliability (due to multiple, redundant stations), and its independence of GPS. The INS/IMU backup was less successful due to its rapid error growth. Although its error growth was considerably smaller, GPS without SA was not able to achieve the TLS for all scenarios primarily because of the failure mode (satellite availability) common to both DGPS and GPS.

## 1.2 Scope/Purpose

The overall purpose of NAAT is to find the rate of occurrence of incidents, i.e., groundings or collisions with the edge of the channel, for an arbitrary scenario consisting of a

- primary and one or more secondary navigation systems with a given use priority sequence; systems include both long-range (e.g., radionavigation systems) and short-range (e.g., visual aids), as well as inertial systems
- navigation area (waterway) with a precisely defined channel configuration and specified currents
- vessel with given dimensions

The incident rate is generally compared to a criterion such as the Target Level of Safety (Creamer, *et al*, 1997) to determine whether the navigation aids available to that navigation area meet the performance specification.

The purpose of Task 1 is to develop a method that is able to quantify both the incident probability and the transition rates for navigation by visual aids. This quantification is necessary so that visual aids can be treated in the same fashion as other

radionavigation systems or onboard sensors. In this way, visual navigation can be integrated into the existing Markov State Space methodology as an independent system, on equal footing with other navigation systems. The user of NAAT has the ability to create various navigation area transit scenarios in which visual aids are included in the suite of navigation systems. Additionally, the user may specify the order of precedence for each system. For example, in a three-tier system, DGPS may be assigned to the top level, visual aids may be designated as number two and a radar system may be set as the third level.

In Task 2, the purpose is to develop a method that dynamically creates a Markov chain based on the navigation systems and parameters specified by the NAAT user. This contrasts with the earlier Markov chain implementations in which the number and priority of the component navigation systems were fixed. The method is structured so that the NAAT user can specify the following elements: type and priority use of the vessel's navigation systems, vessel physical characteristics (including speed), and parameters defining the navigation area. The NAAT operator also has the ability to create a new element or select a pre-defined element type from a catalog.

## 1.3 Objectives

For Task 1, the primary objective is to create a visual aid navigation state, using a technique that logically incorporates a model for calculating incident probability. The visual aid incident calculation must account for factors such as: visibility level of aid, navigation area configuration, vessel size, and the type/location of visual aids. Another objective is to ensure that the technique has a causal connection to the target level of safety (TLS). This requirement enforces consistency between the standard of comparison and computed performance measures. A final objective is to make the technique relatively simple and straightforward so that, when integrated into the overall Markov state methodology, the computational resources will not prevent the NAAT tool from being useful and effective.

The primary objective of Task 2 is to adapt the incident state calculation developed in two earlier efforts (Creamer, *et al*, 1997 and Morris and McGaffigan, 1999a) to the *dynamical* case in which the vessel characteristics, available navigation systems, and specified navigation area parameters are input by the NAAT user. Another objective is to ensure that the technique accounts for factors such as: visibility level, navigation area configuration, vessel size/speed, and the type/placement of visual aids. A final objective is to extend the previously developed one-dimensional analysis to account for two dimensional effects, i.e., turns.

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# 2. Methodology Overview

## 2.1 Task 1 Overview

Here we attempt to quantify the process of visual navigation to permit the visual aid navigation state to be appropriately included in the Markov chain in the same way as any other navigation system (e.g. DGPS, Loran-C, and radar). Incorporation of visual aid navigation into the Markov methodology requires that transitions from the visual aid navigation state to other system operation states and the incident state be defined.

For the visual aid navigation states, system parameters, such as transition rates, may be dynamically set on a segment-by-segment basis The transition rate to lower priority states is determined from the mean aid failure rate. It is assumed that mean time to repair (MTTR) for an aid is of sufficient length such that recovery will not occur within a navigation area transit time. The mean aid failure rate and incident rate for the visual aid state is dependent upon the visibility determined at the beginning of each navigation area segment as follows:

- If any aids are present and visible in the forward direction,
  - ⇒ the transition rate is governed by both the single-aid failure rate and the number of aids visible
  - ⇒ the incident rate is calculated using an empirical TLS model (see Section 3.2.1)

- If no visual aids are visible in the forward direction,
  - ⇒ the transition rate to the system operation state just below visual navigation in priority is sufficiently large so that the transition is effectively deterministic
  - ⇒ the incident rate is that for the next lower-priority system operation state

- If no lower-priority systems are specified, the lowest-priority navigation state, "blind segment navigation," is presumed.

"Blind segment navigation" is a form of dead reckoning in which no visual aids or navigation systems are directly used. The incident probability for this state is computed using the blind segment model (see Section 3.2.2). This model is applied even if aids "behind" the vessel, i.e., not in the vessel's direction of motion, are visible. This is based on the assumption that these aids do not provide equivalent guidance to even a single aid in the forward direction. Thus, aid visibility is computed only in the "forward" direction, i.e., in the direction of the vessel's motion.

Aid visibility, which is treated in more detail in Section 3.1, is based upon the atmospheric visibility throughout the navigation area as well as the range of each visible aid. To limit the possible number of states, only transitions from an "aids visible" condition to a "no aids visible" condition are considered. Designate $\lambda_1$, $\lambda_2$, $\ldots\lambda_n$ as the independent failure rates associated with $n$ visible aids, and label $\mu_1$, $\mu_2$, $\ldots\mu_n$ as the corresponding recovery rates. Then, if the $\lambda$'s are not large, the probability that all $n$ aids fail in a time $\Delta t$, where $\Delta t << 1/\lambda$, is $\lambda_1\lambda_2 \ldots\lambda_n\ (\Delta t)^n$. Thus, for independent failures, the transition failure rate from a state with $n$ visible aids to a state with no visible aids is $\lambda_1\lambda_2 \ldots\lambda_n(\Delta t)^{n-1}$. The unavailability, i.e., the fraction of time that none of the $n$ aids are available, is $(\lambda_1/\mu_1)(\lambda_2/\mu_2)\ldots(\lambda_n/\mu_n)$. Thus, the effective recovery rate is $\mu_1\mu_2\ldots\mu_n(\Delta t)^{n-1}$. In most cases of interest, the recovery time of a failed aid is greater than the vessel transit time through the navigation area. Hence, the $\mu$'s are very small, although $\lambda<\mu$. These results indicate that, for a large number of visible aids, the transition rate to the next lower-priority system operation state is very small.

Figure 2.1-1 shows an example of a Markov chain incorporating visual aids. This figure depicts all of the individual states of a system including Loran-C, visible aids, and radar. The failure rate connections are also shown. The small boxes labeled "INC" refer to the incident state, which can be reached from any other state. Finally, the shading of the visible aid state indicates that it expands into a decision tree.

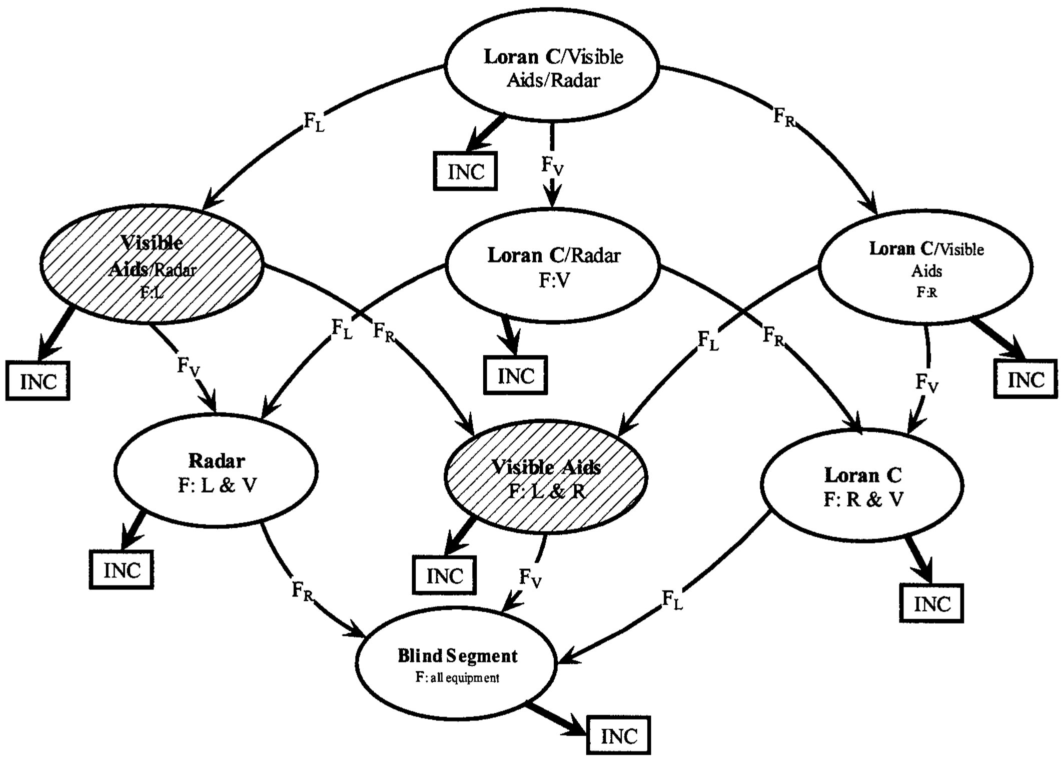


Figure 2.1-1. Incorporation of visual aids into the Markov chain methodology – an example.

Figure 2.1-2, shows the decisions made for the visual aid state that determines which of the incident probability calculations are performed. As noted earlier, if no aids are visible in the forward direction, the transition rate from the visual aid state to the next lower-priority navigation system operation state becomes extremely large, thus effectively causing a deterministic transition. Since the Markov structure is a "chain," a state (or link) cannot be simply removed. However, a state can be effectively removed by assigning an extremely large transition rate from that state.

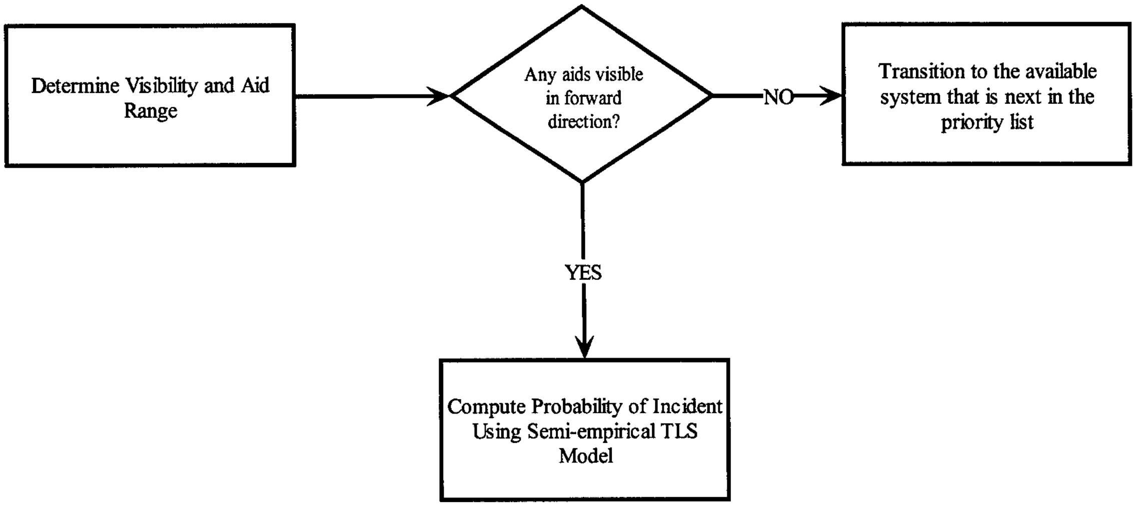


Figure 2.1-2. Decision tree for visual aids state.

## 2.2 Task 2 Overview

The dynamic Markov Chain generation process can be described in four major steps (see Figure 2.2-1):

- Define on-board equipment (user input)
- Generate states to be included in the Markov Chain
- Determine navigation operation mode for each mode
- Determine connections and insert transition rates

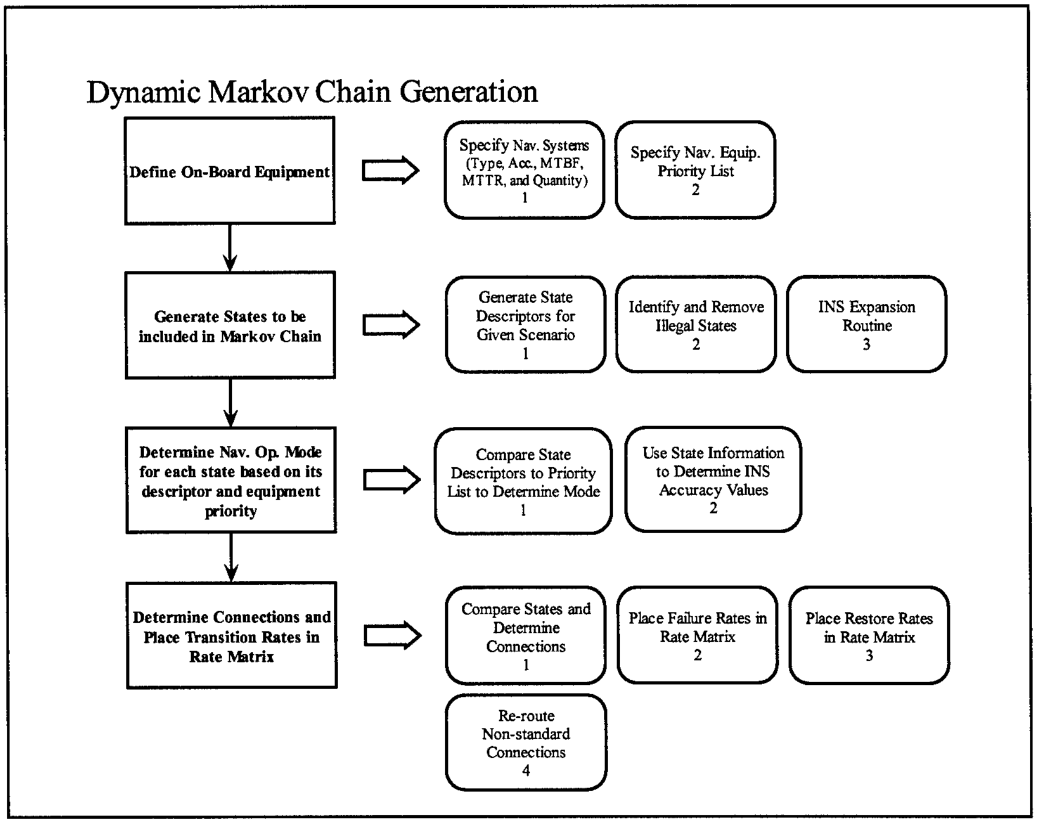


Figure 2.2-1. Dynamic Markov chain generation.

## 2.2.1 First Step: Define On-board Equipment

In the first step, navigation equipment is selected from the following categories:

- DGPS
- GPS
- Loran-C
- INS
- Radar
- Visual Aids
- User-defined

For the selected system, parameters fully defining the system must be specified. These parameters include:

- Accuracy (1-σ value in meters)
- Mean time between failure (MTBF in hours)
- Mean time to restore (MTTR in minutes)
- Quantity (number of systems)

In addition, the order of preference specified by the NAAT user is indicated by means of a numerical ranking attached to each system.

### 2.2.2 Step 2: Generate Markov Chain States

This step consists of four principal actions:

- Generate state descriptors for the selected scenario
- Identify and remove illegal states
- Expand INS states

A 10-bit binary string (see Fig. 2.2-2) serves as the descriptor for the selected suite of navigation systems. This descriptor contains entries for all allowed navigation systems listed above. The bit position code is given by the first letter of one of the navigation systems listed above. When needed (DGPS and Loran-C) a second numerical code indicates how many stations are accessible. Thus, for example, (D2,D1) = (1,1) means that 2 DGPS beacons are available, whereas (0,1) indicates only single beacon availability ((1,0) is disallowed). The binary word represented by the 10-bit descriptor is a *maximum value* for any system state. If {T} is the set of non-zero bit positions (positions 5, 8, 9, 10 in Fig. 2.2.1), the states are represented by 10-bit strings that have a 0 or 1 in the set {T} and 0 in the other bit positions. The number of allowed states is $2^{n(T)}$ ($n(T)$ is the number of elements of {T}) minus any disallowed states (see Fig. 2.2.2). This representation is useful for comparing states to determine the difference in operational navigation systems represented by the states. Thus, if binary words

represented by each of two states differ by a single bit, the states also differ by a single navigation system/service, or equipment item.

| D2 | D1 | G | L5 | L4 | L3 | I | R | V | U |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |

Figure 2.2-2. Navigation system descriptor.

If one of the selected navigation systems is an INS/IMU, then {T} includes the fourth bit position (measured from the right; see Figure 2.2.1). States for which this bit is set are duplicated to emulate the rapid error growth of the INS/IMU (Morris, 1999a). In the earlier work referenced here, the INS error growth was represented by five states to minimize the numerical impact of rapid accuracy shifts. Subsequent testing showed that the impact on the Markov chain calculation is minimal, so that the number of states is reduced to two. The state duplication can be understood by imagining a fictitious eleventh bit position that is zero when the INS/IMU is in the lower initial error condition and one when it is the final error condition (all other bit positions are the same).

### 2.2.3 Step 3: Determine Navigation Operational Mode for each State

First, assume that the state descriptor binary representation (Fig. 2.2-2) is ordered so that the higher-priority systems occupy the higher-order bits. In this way, the priority descends from left to right. For example, if the use priority of Loran-C were higher than GPS, then the three Loran-C states would occupy the slots 3,4 and 5. The navigation operational mode, i.e., the navigation system actually in use while the system is in a particular state, is then normally determined by the navigation system corresponding to

the highest order set bit for that state. Very simply stated, the navigation mode for a particular state is that of the highest priority available system.

| | D2 | D1 | G | L5 | L4 | L3 | I | R | V | U | Nav. Op. Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System Descriptor | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | |
| STATE 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | DGPS 2 Beacons |
| STATE 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | DGPS 2 Beacons |
| STATE 3 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Loran-C 3 Stations |
| STATE 4 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | All Equip. Has Failed |
| | | | | | • • • | | | | | | |
| STATE 11 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Loran-C 3 Stations |
| STATE 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | All Equip. Has Failed |

Figure 2.2-3 State descriptions of the Navigation Operational Mode.

Dependencies between navigation systems, however, do lead to exceptions to this rule. An example is shown in Figure 2.2-3 where State 3 indicates that the left-most non-zero bits are D2 and D1 thus implying a navigation operational mode is 2-beacon DGPS. However, also note that the GPS bit (in bit position 8) is zero, indicating that the constellation is unavailable or the GPS receiver is inoperable. In either case, DGPS, which only provides *corrections* to the GPS signals, cannot be used for navigation. This leaves Loran-C as the highest priority fully functional navigation system — by definition, the navigation operational mode.

The error parameters associated with the INS/IMU state are completely defined only when the priority ranking of the INS/IMU system is specified. This requirement is necessary because the INS/IMU is most commonly used as a transitional, or accuracy-holding, device. In this arrangement, the INS/IMU is slaved to (i.e., continuously corrected by) the next higher system in the priority sequence so that, in the event of failure, INS/IMU either returns operational navigation to that system after a short time or transitions to the next lower-priority state. Since the total time that the INS/IMU can be in the navigation operational mode is short (typically 2 – 10 minutes), the failure probability, while operational, is assumed to be zero. The INS/IMU can, of course, fail at any other time, so that it might not be available when the higher-priority navigation system fails. Figure 2.2-4 illustrates the INS/IMU error growth and the error states, INS 1

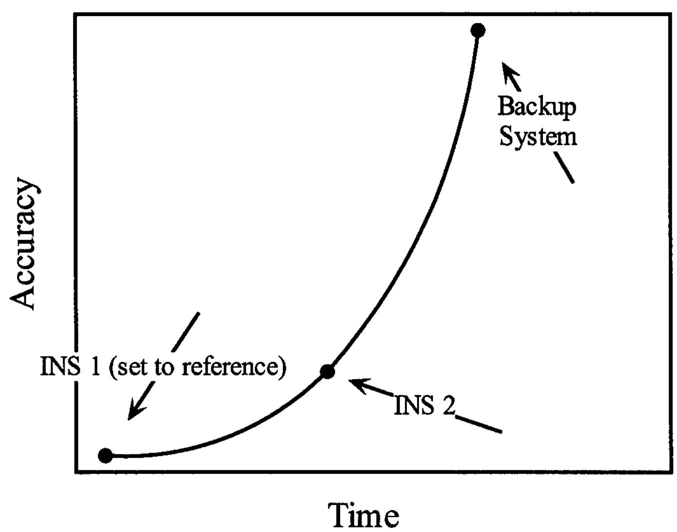


Figure 2.2-4. Error growth and state errors for a given type of INS/IMU.

and INS 2. In the figure, "reference" refers to the accuracy of the next higher-priority system and "backup" indicates the next lower-priority system. The dwell time in each state depends on the type of INS/IMU (Morris, 1999a). The inverse of the dwell time yields the transition rate. In contrast to the previous discussion concerning INS/IMU *failures*, this transition (from one error state to another) is due to the characteristic error growth of the inertial system. If $\sigma_0$ is the two-dimensional standard deviation associated

with the more accurate preceding system and $\sigma_F$ is that associated with the less accurate following system, then the transition rate for each of the two error states is given by

$$\frac{2\lambda_I}{\ln(\sigma_F / \sigma_0)}$$

where $\lambda_I$ is the exponential error growth parameter for INS/IMU type $I$. For the low-end INS/IMU (Morris, 1999a), $\lambda_I = 0.0137$ sec$^{-1}$, for the mid-range INS/IMU, $\lambda_I = 0.0092$ sec$^{-1}$, and for the high-end INS/IMU, $\lambda_I = 0.0045$ sec$^{-1}$. The initial state has an error of $\sigma_0$, i.e., the same as the preceding system, while the error associated with the second error state is the same as the error at the mid-time point (see Figure 2.2-4). This error can be expressed as $\sqrt{\sigma_0 \sigma_F}$ , i.e., the geometric mean of the preceding and following system error standard deviations.

### 2.2.4 Step 4: Generate Dynamic Markov Chain

To generate the dynamic Markov chain, the chain topology must be cast into a form that is recognizable by the program code. This is done by establishing connections, i.e., identifying states that differ by a single transition. In the binary word representation of states, states are connected if they differ by a single bit.

For those states that are connected, failure and restoral transition rates corresponding to the state transition are entered appropriately into the overall rate matrix. An example of a state connection is shown in Figure 2.2-5. As configured, the initial state describes a vessel's navigation suite containing a GPS/DGPS receiver utilizing corrections from two DGPS beacons, a Loran-C receiver processing Loran-C signals from three Loran-C stations, and a marine radar. The second state is identical, except that only one DGPS beacon is accessible, due to failure of the other beacon. The transition rate in the forward direction is the failure rate, i.e., the reciprocal of the mean time between failure of the DGPS service, typically 1000 hours. In the reverse direction, the transition rate is the restoral rate, which is the reciprocal of the recovery (or repair) time.

The recovery time is typically ten minutes, so if a failure does occur, the service is usually rapidly restored.

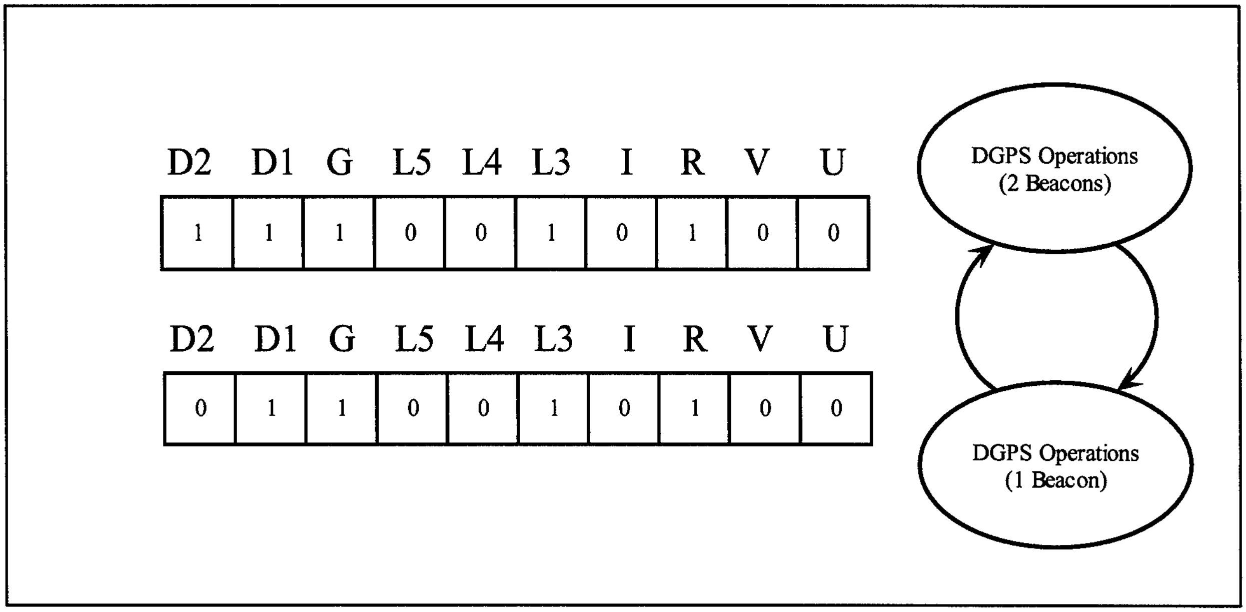


Figure 2.2-5. Example of two-way transitions.

Although the above procedures describe the general rules for state connections and transition rate assignments, there are exceptions that must be addressed. These exceptions occur in connection with the INS/IMU states, as shown in Figure 2.2-6. In this figure, the DGPS – INS 1 connection is standard in that there is a two-way transition between the states. The connection between states INS 1 and INS 2, however, is exceptional in that there is no recovery between the states. There *is* a recovery back to the DGPS state (as there was with INS 1), but the unaided INS error cannot decrease, thus leading to the observed asymmetry. Similarly, there is no recovery between the two connected states: INS 2 and Backup System. Note that the recovery in this case jumps *two* states because it is assumed that INS/IMU cannot be reinitialized without an external system.

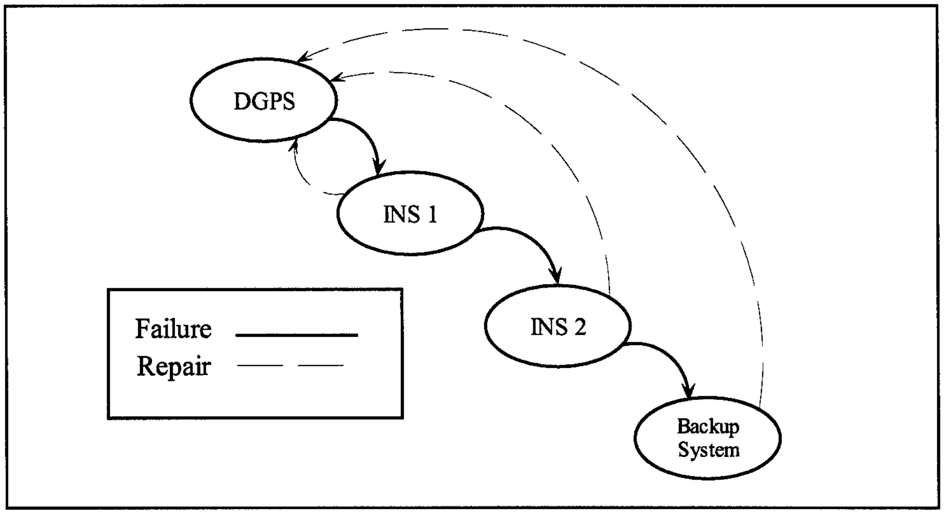


Figure 2.2-6. Example of non-standard state connections/transitions.

## 2.2.5 Task 2 summary

The NAAT implementation has resulted in a dynamically constructed Markov chain as described. A key assumption is that the transitions between states are seamless and without any performance degradation. This is not necessarily analogous to actual operations where there may be a period of reorientation as a mariner switches their attention to a new system. It would depend on the degree that the mariner anticipated a change and prepared for it. Integrated navigation systems may be more accurately represented by this approach.

# 3. Visual Navigation: Parameters and Incident Rate Calculation

The NAAT models radionavigation systems as described in Creamer, et al 1997 and Morris, P. and McGaffigan, D. 1999a. For the completion of NAAT a visual aid model needed to be developed and is described here.

## 3.1 Aid Visibility

Atmospheric visibility of an aid can be expressed either with a visible range, $v$, or as transmissivity, $T$. The two are equivalent and are related as follows:

$$T^v = 0.05 \ (0 < T < 1)$$

where $v$ is given in nautical miles. For transmissivity values from 0.1 to 0.95, the corresponding visibility range varies from 1.3 to 58.4 n.m.

In order for a particular aid to be visible, two conditions must be satisfied. First, the visibility range must be greater or equal to the distance to that aid and, second, the aid range must be greater or equal to the distance to the vessel (see Figs. 3.1-1 and 3.1-2). These conditions may be expressed as

$$v = D(A,x) \text{ and } R(A) = D(A,x)$$

where $D(A,x)$ is the distance between aid $A$ and point $x$ in the navigation area and $R(A)$ is the stated range of aid $A$.

Figures 3.1-1 and 3.1-2 illustrate some likely configurations in which aids may be visible or not. Figure 3.1-1 shows the case where two aids are placed on the navigation area, but only Aid 1 falls within the visibility radius of point $X$.

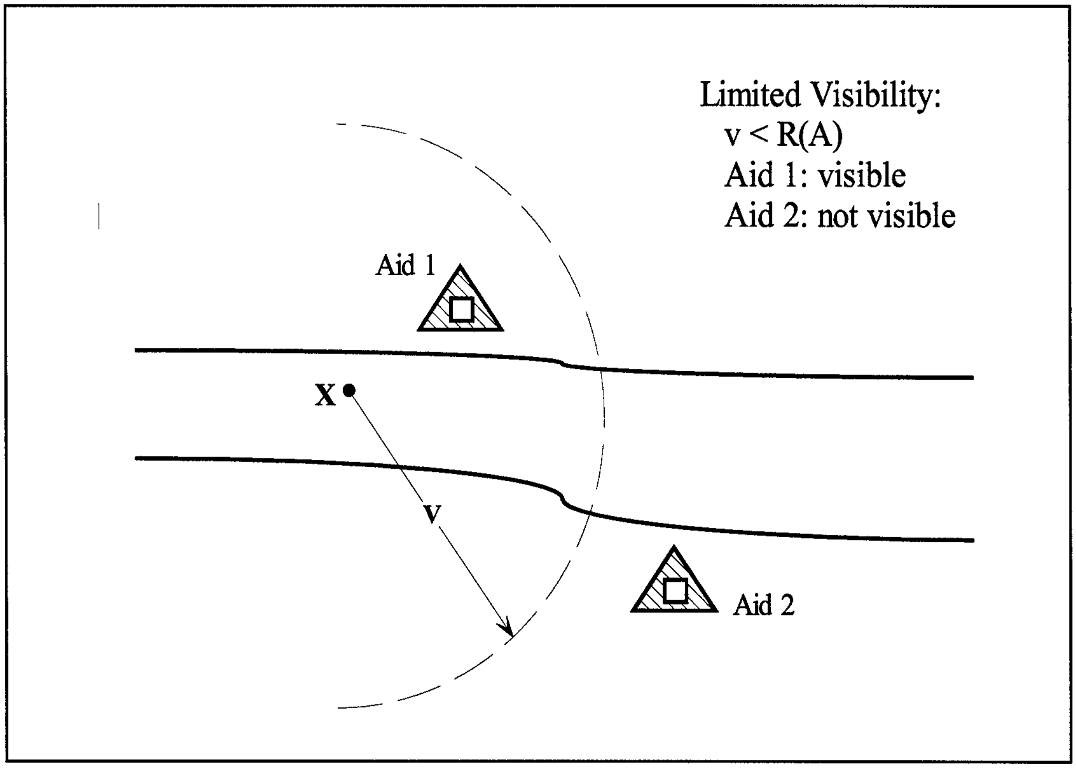


Figure 3.1-1. Limited visibility example.

Figure 3.1-2 shows the case where the aid is enclosed in the atmospheric visibility circle, but the aid range is insufficient so it cannot be seen at location *X*.

For vessels navigating a navigation area strictly by means of visual aids, calculation of the incident probability is difficult because the relationship between the pilot's control of the vessel and his use of visual aids is hard to quantify. In fact, for the general situation in which multiple aids of different types are visible on either or both sides of the channel at various distances from the vessel, detailed calculation of the incident probability is judged impractical because:

- Guiding a vessel through the channel using visible aids is an extremely complex coordination of eye, brain, and motor coordination modified by training, skill, and experience

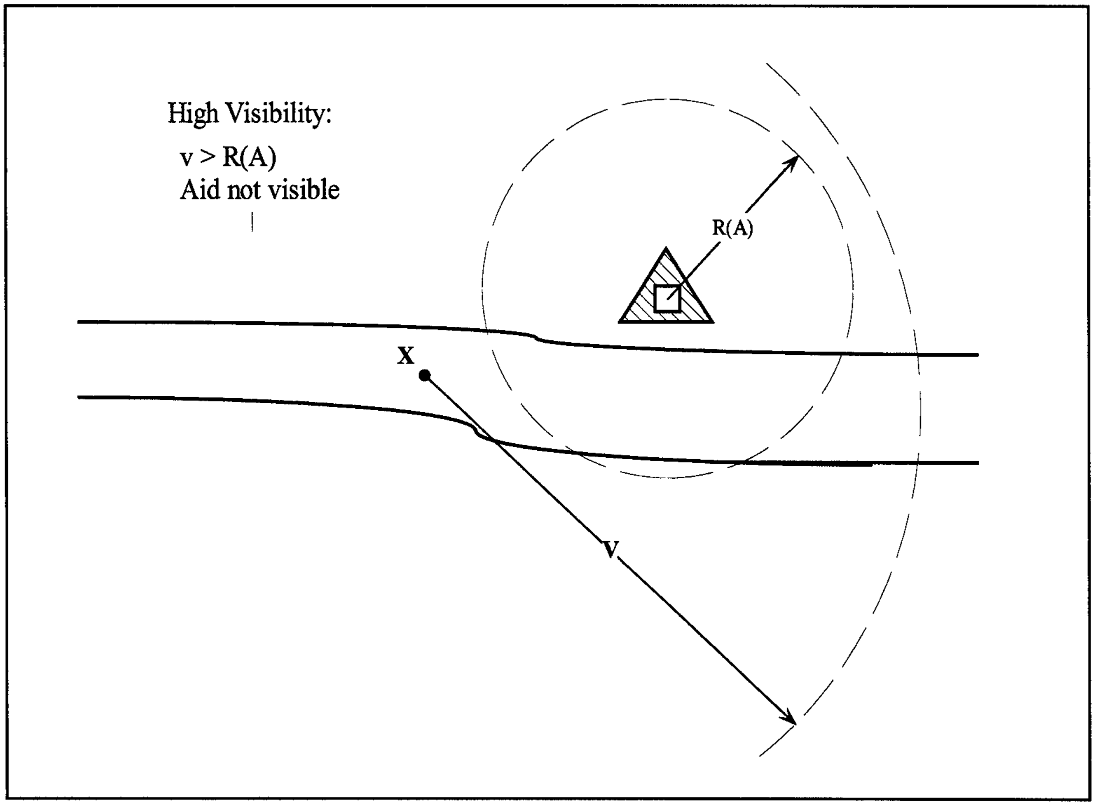


Figure 3.1-2 High visibility example.

- Even comprehensive bio-kinetic models would have difficulty in establishing consistency between "first principles" calculations and the target level of safety since the precise parameters of an incident (grounding) are not well established.
- The failure modes, i.e., the general conditions under which an incident would occur, are incompletely known, especially under benign circumstances

For these reasons, we select an empirical model for the calculation of incident probability when visible aids are present and a dead reckoning- based "blind-segment" model for situations in which no aids are present.

## 3.2 Empirical TLS-based Incident Probability Model

As discussed above, an empirical model is used because direct methods are considered intractable for the purposes of this work. Also, a method invoking a direct connection to the TLS is needed, since the incident probability calculations are routinely compared to the TLS itself. The empirical model accomplishes this by using relationships derived from the same accident database used to calculate the TLS. Thus, the empirical relationship between accident risk and channel complexity parameters (Maio, 1991 and Kite-Powell, 1998) serves as a basis for the empirical model used here.

Use of the empirical relationship between accident risk and channel complexity factors in the calculation of incident probability for visual aid navigation implicitly assumes the following points:

- Most of the vessel traffic addressed by the historical data (Maio, 1991) used visual navigation; thus navigation-related incidents are traceable to the use of visual aids.
- The navigation-related subset of all accidents that was used to calculate the TLS has the same relationship to channel complexity parameters as the full set of accidents.

For the purposes of this work, the following channel complexity parameters, selected from those available in the literature (Kite-Powell, 1998) are enlisted in the empirical model:

1. Approach to the navigation area: open or otherwise
2. Type of navigation area: constricted or otherwise
3. Length of navigation area as measured along the channel centerline
4. Mean channel width in the navigation area

5. Total of all heading changes due to turns in the navigation area

The incident rate for a navigation area was found to be reasonably well correlated with these channel complexity factors and much less with other factors that were tested (Maio, 1991 and Kite-Powell, 1998). Thus, for a given navigation area, the incident rate is much smaller for an open approach than for other types of approaches. Similarly, the risk of incident for a navigation area classified as constricted is considerably higher than that for other navigation area classifications. The last three complexity factors mean incident risk is higher with channels that are longer, narrower, or having more turns than an "average," or "typical" channel.

These characteristics are synthesized and quantified as an incident probability function linear in the complexity factors and non-linear in the number of visible aids. Specifically, the incident rate (number of incidents per segment for vessels moving at speed $v$) for segment $i$ in a specified navigation area is given by

$$ {}_i = \alpha\,\mathrm{TLS} + \beta\left[\frac{\gamma}{N} + \sum_{j=1}^{3}\varepsilon_j(F_{ij} - \overline{F}_j) + \Gamma(n_{Ai})\right] $$

Each of the symbols appearing in this expression is defined below

$\alpha = (L_w/v)/N$ ; $L_w$ = length of navigation area ; $v$ = average vessel speed

$N$ = no. of segments ; TLS = target level of safety (inc/hour)

$\beta = 10^{-5}$ ; $\gamma = (-3.5297/\mathrm{N})\delta_{A,1} + (16.3277/\mathrm{N})\delta_{C,1}$

$F_{i1}$ = length of segment $i$ ; $F_{i2}$ = width of segment $i$

$F_{i3}$ = turn angle if segment $i$ is a turn segment

$\overline{F_1} = \overline{L_w}/N$ ; where $\overline{L_w}$ is the average navigation area length over the entire *Port Needs Study* database

$\overline{F_j}$ = for $j$ = 2, 3, average of $F_{ij}$ over the entire *Port Needs Study* database

$\varepsilon_j$ = sensitivity coefficient for channel complexity factor $j$ (from *Port Needs Study* regression analysis)

$\Gamma = \Gamma_0$ {erfc [0.5*($n_{Ai} - \overline{n}_A$)] – 1} ; where $\Gamma_0$ is an adjustable parameter, $n_{Ai}$ is the number of aids visible at the beginning of segment $i$, and $\overline{n}_A$ is the average number of aids visible

Note that the terms $\alpha$ and $\gamma$ generally depend on the navigation area, whereas terms with subscript $i$ depend on the properties of segment $i$. Other terms that depend on averages over the *Port Needs Study* database will have default values (derived from that database) or can be inputted by the NAAT user. Note that the complexity factors indexed in the expression for incident rate (with indices 1, 2, 3) correspond to the last three factors (3, 4, 5) in the list above. The first two factors in the list serve to compute the intermediate parameter $\gamma$, which is, for example, –3.5297/$N$ if the navigation area approach is open ($A$=1) and the navigation area is unrestricted. The $\delta$ 's appearing in the expression for $\gamma$ are Kronecker delta functions, i.e., unity if the two indices are equal and zero otherwise. The sensitivity coefficients are given by:

$$\varepsilon_1 = 0.2285 \text{ n.m.}^{-1}; \quad \varepsilon_2 = -0.000407 \text{ m}^{-1}; \quad \varepsilon_3 = 0.01212 \text{ deg}^{-1}$$

The form of the empirical expression is such that the segment incident rate is equal to the TLS (scaled to convert from number of incidents/hour to number of incidents/segment) for the case in which the navigation area is not constricted, does not have an open approach, and all segment parameters are equal to average values. Here "average" means the result of averaging over the entire Port Needs Study database. Deviations from these average values cause the incident rate to vary above or below the TLS. For example, a narrower than average navigation area segment would yield an incident rate larger than the TLS, the exact amount depending on the deviation from the average value and the sensitivity coefficient $\varepsilon_2$.

## 3.3 Blind Segment Incident Model

The so-called "blind segment" Incident Model is invoked when visibility conditions are such that no aids are visible to the reference vessel or when all aids visible at a given time are not functioning. The decision to invoke the blind segment incident model is made at the beginning of each segment and is also invoked when all navigation

systems in the vessel's suite have failed — even if visual navigation is not one of the systems selected by the NAAT user.

The model attempts to emulate the navigation of a vessel using only dead reckoning with uncertain initial position and heading. The following assumptions are made regarding the initial conditions and subsequent motion of the vessel throughout a given segment or set of segments:

- Initial vessel position is normally distributed about the channel centerline with a default or user-selected standard deviation
- Direction of vessel motion is normally distributed about 0° with a default or user-selected standard deviation
- Once initiated, vessel motion continues in a straight trackline until the interface with the following segment or until intercepting the edge of the channel (incident)
- The angular distribution is offset (biased) by the vessel's crab angle as the result of any currents assigned to the segment

Figure 3.3-1 illustrates the blind segment model initial conditions and subsequent motion.

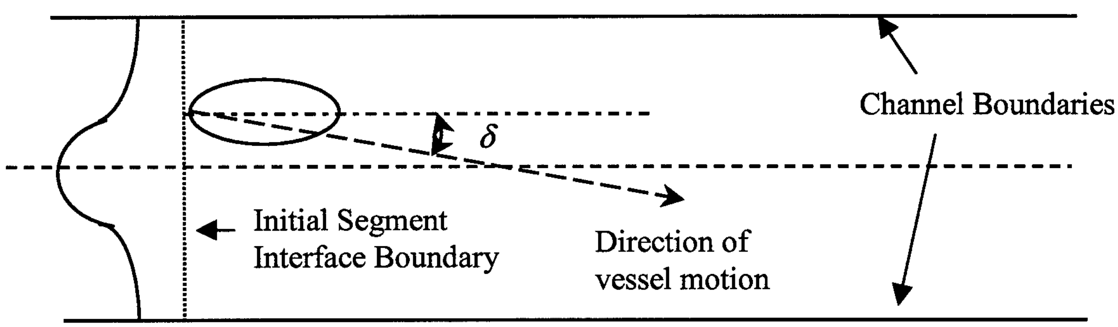


Figure 3.3-1. Blind segment incident model: illustration of uncertain initial position and heading.

In this figure, the curve to the left of the initial segment interface boundary indicates the normal (or Gaussian) distribution of the initial cross-track position of the vessel as it enters the segment. The elliptically shaped object to the right of the initial segment interface boundary and above the centerline represents an equi-probability contour for the heading angle $\delta$ with respect to the dashed line parallel to the channel axis. The probability of the heading angle $\delta$ is proportional to the distance between the point at the

extreme left end of the ellipse and the intersection of the vessel's velocity vector and the ellipse. The actual length of these line segments is Gaussian distributed.

The probability that an incident occurs in the segment is illustrated in Figure 3.3-2. For the initial cross-track position shown, an incident occurs within the segment if the

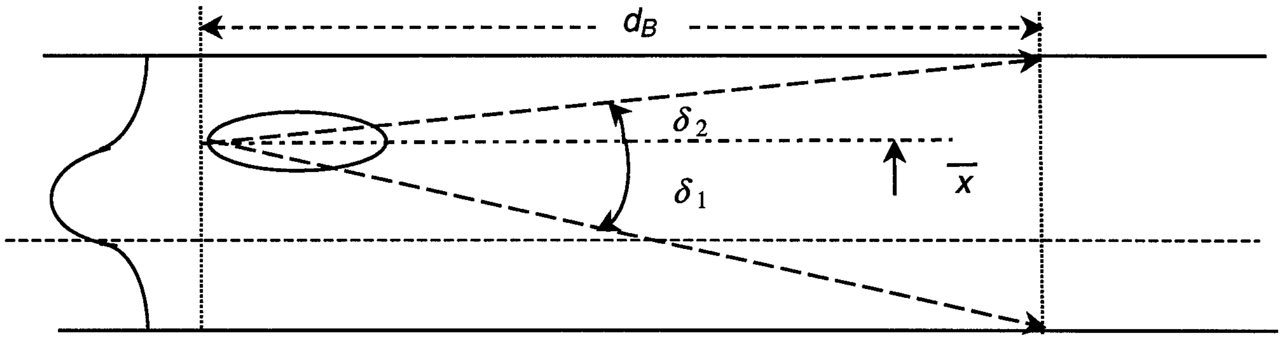


Figure 3.3-2 Incident probability calculation using the blind segment model.

heading is greater than $*_2$ (positive angle) or less than $*_1$ (negative angle). Thus, the probability of an incident is just the integral of the density function over the same angular domain and over all initial positions in the channel at the initial interface segment boundary. The analytic expression for the probability of an incident within the segment (but not at the initial interface boundary) is given by

$$P(incident) = 1 - \left[ \sigma_{x_0} \sqrt{2\pi}\, \mathrm{erf}\left( \frac{x_{FHC}}{\sigma_{x_0}\sqrt{2}} \right) \mathrm{erf}\left( \frac{\pi}{2\sigma_\delta \sqrt{2}} \right) \right]^{-1} \int_0^{x_{FHC}} \mathrm{erf}\left[ \frac{\arctan\left( \frac{x_{FHC} - \bar{x}}{d_B} \right)}{\sigma_\delta \sqrt{2}} \right] e^{-\frac{\bar{x}^2}{2\sigma_{x_0}^2}}\, d\bar{x}$$

# 4. Navigation Area and Vessel Specification

To facilitate the execution of NAAT, data concerning commonly used vessel characteristics and navigation areas are stored in "catalogs." This makes it easier for the NAAT user who wants to make many runs with a variety of commonly used vessels and navigation areas. New vessels and navigation areas have to be created "from scratch," of course, but can then be added to the catalogs for future, quicker use.

## 4.1 Vessel Specification

The vessel catalogs include only cursory information on standard types of vessels. The information includes vessel type, length, and beam. Vessel operating speed is input as part of the Segment Editor since vessel speed may change from segment to segment. Table 4.1-1 provides an abbreviated example of a vessel catalog.

Table 4.1-1. Sample vessel catalog.

| No. | Type | Length (ft.) | Beam (ft.) |
|---|---|---|---|
| 1 | 33 k Tanker | 574 | 85 |
| 2 | 1000' Great Lakes Ore Carrier | 990 | 105 |
| 3 | 76 k Bulk Carrier (Panamax) | 855 | 106 |
| 4 | 150 k Coal Carrier | 915 | 145 |
| 5 | 250 k Tanker | 1085 | 170 |

The length and width data, together with the current information, is used to determine the free half-channel width (see Section 4.2.4) that is needed for the incident rate calculation. Also note that the speed in a turn, which may be chosen by the NAAT operator, generally differs from that in the straight segments (see the next section).

## 4.2 Navigation Area Specification

As with vessels, the navigation areas analyzed by NAAT may be selected from a catalog of previously modeled navigation areas or created as an entirely new navigation area. Navigation area information is categorized as three general types:

- Turn point data
- Segmentation data
- Visual aid data

### 4.2.1 Turn Point Data

In general, the turn point data includes:

- latitude/longitude of the turn point
- angle of the turn
- speed in the turn
- distance in the turn
- turn radius of curvature

The turn point is defined as the intersection of the extended channel centerlines preceding and following the turn. The final two items are not generally input by the NAAT operator, i.e., default values are provided.

### 4.2.2 Segmentation Procedure and Data

The turn point data, together with the starting and end point positions (included with the segmentation data), determine the two-dimensional configuration of the channel centerline. The segmentation data provides the additional information necessary to specify the channel geometry and other characteristics. This data includes:

- coordinates of the reference point for each segment
- length of each segment (if not all segment coordinates specified)
- width at the reference point for each segment (and at the end of the last segment)
- current speed and direction at each segment

- vessel speed at each segment.

The channel centerline is principally described by a series of straight lines (actually arcs of great circles) connecting the coordinates (latitude/longitude) of the navigation area beginning and end-points, and the coordinates of each point characterizing a turn, as illustrated in Figure 4.2-1 (lower panel). The channel width may be thought of as a function of the channel centerline distance from the transit start as in Figure 4.2-1 (upper panel).

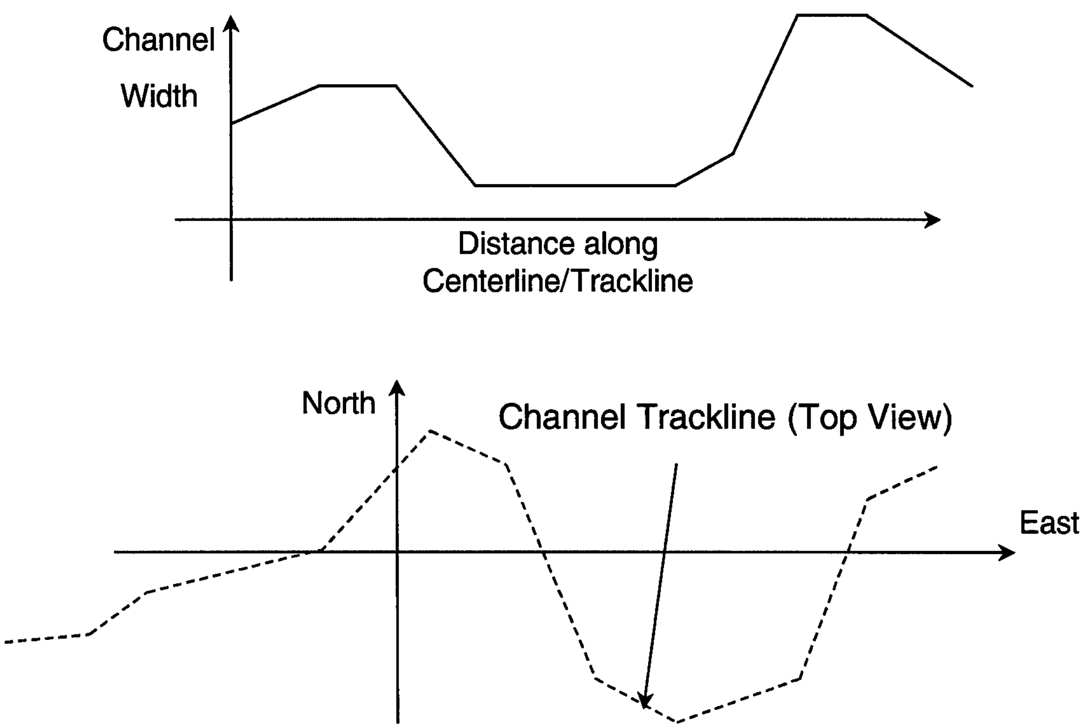


Figure 4.2-1. Examples of navigation area description input.

The reference point for each straight segment is the intersection of the channel centerline and the initial interface boundary, as illustrated in Figure 4.2-2. This figure shows a general configuration for segments along a straight portion of the channel. Note that the interface boundaries generally differ in size (channel width) but are always perpendicular to the channel centerline. Once the two-dimensional configuration of the navigation area

is established, it is broken into segments whose lengths (along the centerline) must satisfy the following requirements:

1. The segment length is much larger than the channel width.
2. The length is short enough such that the channel characteristics vary little over the segment (e.g. visibility and orientation).

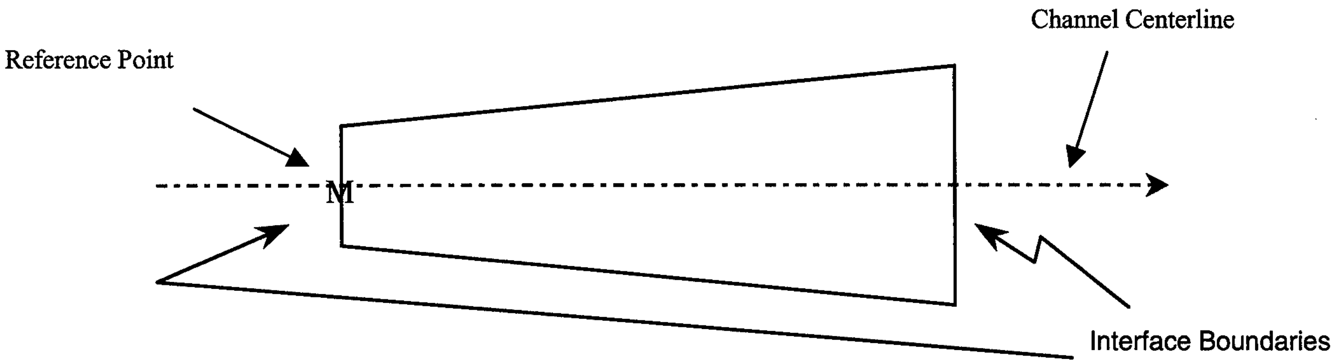


Figure 4.2-2. Segment configuration in the straight portion of the channel.

In contrast to the straight channel segments described above, turn segments do not have parallel interface boundaries (see Figure 4.2-3). The turn segment itself is a quadrilateral whose interface boundaries meet at an angle equal to the turn angle ($\theta$) and bisected by the bisector of the turn angle supplement (note that $\pi - \theta = 2\phi$). The reference point for this segment, i.e., the point defined by the turn point coordinates, is the intersection of the channel centerlines (extended) preceding and following the turn segment. This is to be contrasted with the reference point for a straight segment, whose coordinates are given by the intersection of the channel centerline and the segment's initial interface boundary. The "width" of the turn segment is given by the average of the segment's initial interface boundary and final interface boundary widths.

To simplify the process of creating a new navigation area, a segmentation algorithm has been built into NAAT to compute an initial segmentation structure, based on an assumed range of "reasonable" segment lengths. The algorithm will also initially assume a fixed channel width (based on NAAT operator input). Application of this algorithm will create a complete navigation area specification with minimal effort by the NAAT operator. Ultimately, however, the NAAT operator will have complete control of the navigation area specification through the editing of the position, length, and width of any and all segments. Alternatively, the NAAT operator may wish to input segment coordinates and widths from a database.

As an example of this input, a navigation area description was created for Tampa Bay and is shown in Table 4.2-1. The data was obtained from a large-scale (1:40,000) NOAA chart of the area. The "Segment ID" in the first column of the table uniquely identifies both a point and a segment. The point refers to the midpoint of the initial interface boundary of the segment (assuming a definite direction for the vessel) so there is a one-to-one correspondence between all points and segments except for the last segment. This is because a segment lies between two points, but because the second point

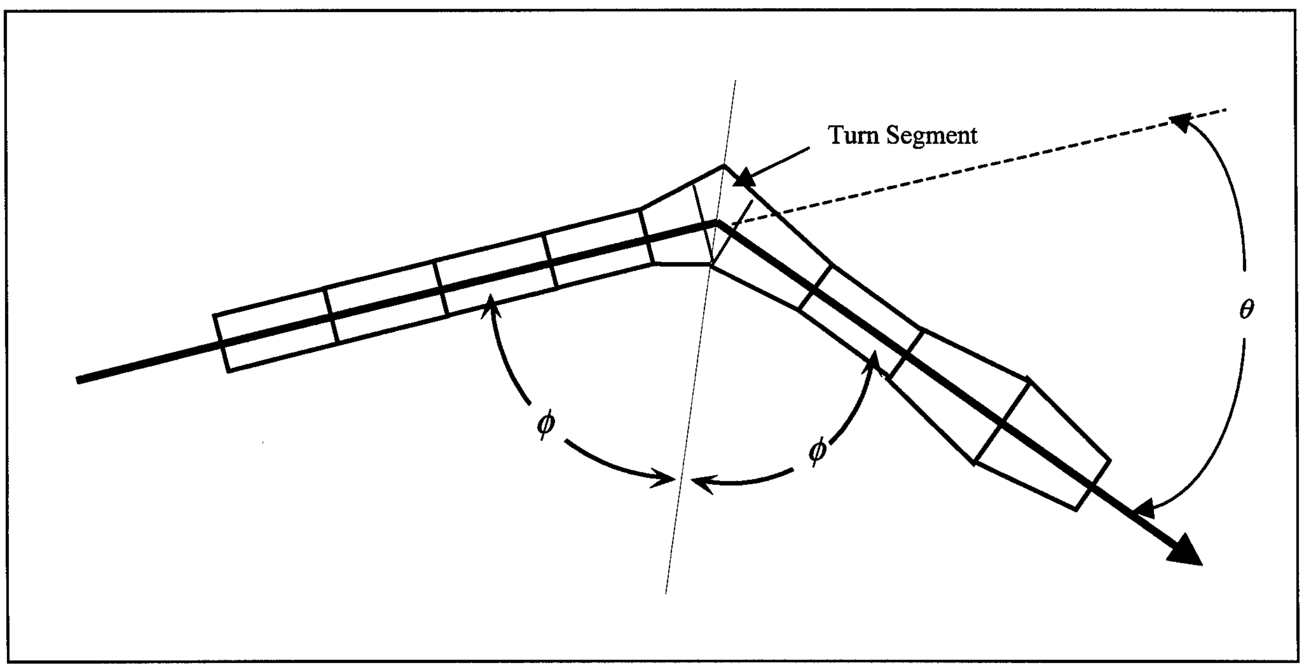


Figure 4.2-3. Illustration of the turn segment in relation to the straight channel segments.

Table 4.2-1. Sample Tampa Bay channel description.

| **Segment ID** | **Latitude** (degrees) | **Longitude** (degrees) | **Width 1** (feet) | **Width 2** (feet) | **Description** |
|---|---|---|---|---|---|
| 1 | 27.6047 | 82.7244 | 600 | N/A | start point |
| 2 | 27.6133 | 82.6705 | 500 | 500 | turn point |
| 3 | 27.635 | 82.6244 | 500 | 500 | turn point |
| 4 | 27.6581 | 82.6038 | 550 | N/A | straight segment/diff. width |
| 5 | 27.6817 | 82.5846 | 500 | 500 | turn point |
| 6 | 27.694 | 82.564 | 500 | 500 | turn point |
| 7 | 27.7242 | 82.5353 | 500 | 500 | turn/start of last segment |
| | 27.7569 | 82.5231 | 500 | N/A | end of last segment |

is always the first point of the next segment, the relationship is always one-to-one, except for the last segment, which has no following segment. Thus, the table has two points (rows) listed for the last segment ID. The columns labeled "Width 1" and "Width 2" refer to the segment widths (measured normal to the channel axis) at the points just preceding (Width 1) and just following (Width 2) the turn segment. Note, finally, that Segment ID 4 in Table 4.2-1 does not refer to a turn point, but rather to a point where the channel width has a local maximum of 550 feet. Thus, segment 3 has an initial width of 500 feet and a final width of 550 feet, whereas Segment 4 has an initial width of 550 feet and a final width of 500 feet.

The resulting centerline is plotted in Figure 4.2-4. Here the latitude and longitude have been converted to a consistently scaled local Cartesian system by multiplying the longitude intervals by the cosine of the latitude.

A second navigation area catalog was created for the St. Mary's River/Rock Cut. The corresponding table description for this navigation area is given in Table 4.2-2 and the channel is plotted in Figure 4.2-5

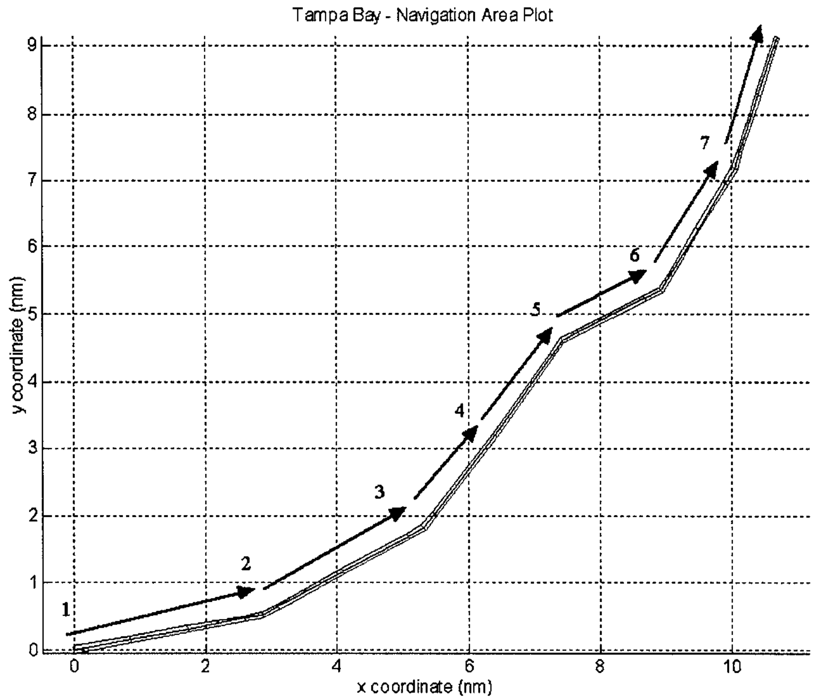


Figure 4.2-4. Pot of centerline for Tampa Bay.

Note that, in both these scenarios, we picked a specific transit direction. Had we picked a different direction, the coordinates would remain the same, the segment IDs would be reverse-ordered, and widths 1 and 2 would be interchanged.

### 4.2.3 Visual Aid Data

In addition to the navigation area segment data described above, the NAAT operator, who wishes to include visual navigation as one of the vessel navigation systems to be studied, is required to input the coordinates (latitude and longitude) of all visual aids. Each visual aid is specified by its type, visible range in day, visible range at night, as well as the aid's reliability parameters (MTBF and MTTR). The information is most easily input using a structured file, such as that produced by Microsoft®Excel.

Table 4.2-2. St. Mary's River/Rock Cut channel description.

| Segment ID | Latitude (degrees N) | Longitude (degrees E) | Width 1 (feet) | Width 2 (feet) | Description |
|---|---|---|---|---|---|
| 1 | 46.3809 | 84.2272 | 300 | NA | start |
| 2 | 46.3536 | 84.2133 | 600 | 600 | turn |
| 3 | 46.2881 | 84.215 | 600 | 600 | turn |
| 4 | 46.258 | 84.1833 | 700 | 700 | turn |
| 5 | 46.2223 | 84.1716 | 760 | 680 | turn/start of last segment |
| | 46.1851 | 84.1057 | 300 | NA | end of last segment |

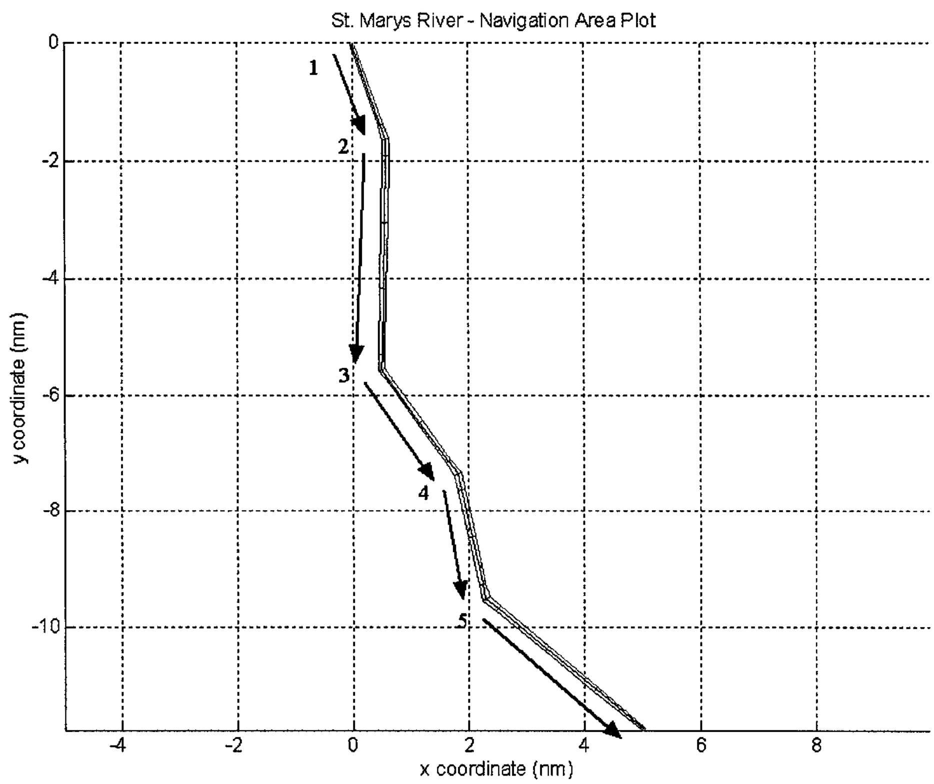


Figure 4.2-5. Plot of St. Mary's River/Rock Cut.

A sample aid list is shown in Table 4.2-3. Although the list is abbreviated from its original form that had additional fields, it contains most of the essential visual aid data required by NAAT. The table shows aid name, type, and latitude/longitude in decimal degrees. Day ranges in nautical miles are given for most aids and night ranges are specified in nautical miles for lighted aids. The last column lists the availability of the

Table 4.2-3. Partial visual aid list for Tampa Bay.

| AID NAME | LONGITUDE | LATITUDE | AID TYPE | Day Range | Night Range | Availability |
|---|---|---|---|---|---|---|
| SW Ch Ent LBB 1 | -82.79816 | 27.54198 | LB | 3.2 | 4.0 | 97.9% |
| Tampa Bay LWB T | -83.01180 | 27.58866 | LB | 3.2 | 6.0 | 97.9% |
| Manatee Riv LT 2 | -82.67828 | 27.54373 | LT | 1.0 | 3.0 | 97.9% |
| Manatee Riv Cut A RFL 4 | -82.66884 | 27.53513 | LT | 0.0 | 3.0 | 97.9% |
| Manatee Riv Cut A/C RRL | -82.66632 | 27.53279 | LT | 2.0 | 0.0 | 97.9% |
| Manatee Riv Cut C RFL 6 | -82.66267 | 27.53222 | LT | 1.0 | 3.0 | 97.9% |
| Manatee Riv LT 7 | -82.65067 | 27.53057 | LT | 1.0 | 3.0 | 97.9% |
| Manatee Riv DBN 8 | -82.65083 | 27.53001 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 9 | -82.64819 | 27.52928 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 10 | -82.64405 | 27.52698 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 11 | -82.64172 | 27.52671 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv LT 12 | -82.64064 | 27.52556 | LT | 1.0 | 3.0 | 97.9% |
| Manatee Riv LT 14 | -82.61892 | 27.51749 | LT | 1.0 | 3.0 | 97.9% |
| Terra Ceia C/O DBN 2 | -82.61222 | 27.52203 | DBN | 1.0 | 0.0 | 97.9% |
| Terra Ceia C/O DBN 4 | -82.60634 | 27.52932 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv LT 15 | -82.60847 | 27.51256 | LT | 1.0 | 4.0 | 97.9% |
| Manatee Riv DBN 16 | -82.58274 | 27.50943 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 18 | -82.58054 | 27.50898 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv LT 19 | -82.57887 | 27.50960 | LT | 1.0 | 3.0 | 97.9% |
| Manatee Riv DBN 20 | -82.57734 | 27.50590 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 21 | -82.57464 | 27.50401 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 24 | -82.55869 | 27.50441 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 23 | -82.55890 | 27.50479 | DBN | 1.0 | 0.0 | 97.9% |
| Manatee Riv DBN 24A | -82.55457 | 27.50565 | DBN | 1.0 | 0.0 | 97.9% |

aid, which is usually given as the nominal requirement: 97.9%. As noted above, NAAT requires not the availability, *per se,* but the MTBF and MTTR separately. In practice, NAAT assumes that the MTTR is longer than a navigation area transit time and thus need not be explicitly given. If the NAAT operator knows only the availability, however, one can estimate the aid MTBF by assuming a reasonable MTTR of, say, 24 hours, and computing MTBF = MTTR / Availability. In its current form, NAAT input for aid reliability is separate from the aid data, since the aids are assumed to have the same MTBF and MTTR. If no reliability data is provided, NAAT inserts a default value of 1000 hours for the aid MTBF and $MTTR^{-1} \cong 0$.

### 4.2.4 Effective Free Half-Channel

For most navigation areas, the channel geometry dictates that a transiting vessel cannot be treated as a point object. In fact, the length of a large vessel (such as a Great Lakes carrier) is a significant fraction of (or even greater than) the channel width. If the vessel always maintains its axis parallel to the channel, then the beam-to-channel width ratio (generally not too large) is the important parameter in computing incident rate.

However, wind and/or current cause the vessel to be inclined at a *crab angle* so that the vessel's actual velocity vector (with respect to the earth) is parallel to the channel axis. In general, the crab angle, *2*, is given by

$$\tan\theta = \frac{c_y}{c_x - v_x}$$

where $c_y$ , $c_x$ are the cross-track and along-track components of the current velocity, respectively. The quantity $v_x$ is the vessel's resultant velocity along the channel axis.

With a non-zero crab angle, effective vessel width, or beam, $W_{eff}$ is easily seen to be (see Figure 4.2-6)

$$W_{eff} = L\sin\theta + W\cos\theta$$

This effective beam for the vessel leads to an effective free half-channel (see Figure 4.2-6) of

$$X_{EFHC} = \frac{X_C - (L\sin\theta + W\cos\theta)}{2}$$

where $X_C$ is the channel width, measured perpendicular to the channel axis.

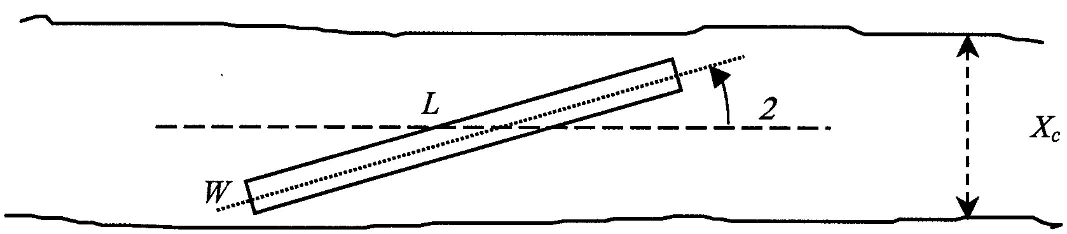


Figure 4.2-6. Vessel-channel geometry for effective free half-channel calculation.

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# 5. Incident Rate Calculations for Turns

For navigation systems other than visual aids, the following features characterize the current incident model:

- ECDIS-like guidance of the vessel in which both the actual and desired tracks are displayed
- Assumed guidance/control of a vessel in attempting to maintain a desired trackline results in a sinusoidal variation about the intended trackline.
- Sinusoid amplitude and frequency determined from King's Point data; phase model is based on a random walk Wiener process
- An incident rate that depends only on the cross-track extent of the channel boundaries relative to the channel axis.

This one-dimensional model can be applied to individual non-parallel straight-line segments but must be revised and extended to handle the *transitions* between non-parallel straight portions, i.e., turns.

## 5.1 Turn Model and Geometry

Extending this control model to turns implies coordinated actions between three principal regimes:

1 Pre-turn straight segment
2 Turn segment
3 Post-turn segment

In the first regime, the vessel is initially in a "straight-channel" mode in which its trajectory wavelength is long and the velocity along the channel direction is at operating speed, typically 10 knots. As the vessel enters the turn segment, the speed is reduced and the sinusoid wavelength is shortened, reflecting the need for increased control. The actual trackline in the turn segment may be approximated as the arc of a circle. Thus, the amplitude of the trajectory is expected to increase because the reference trackline is

constantly changing direction. Finally, as the vessel enters the third regime, the speed and wavelength begin to increase and eventually return to initial pre-turn segment values. The trajectory amplitude would also return to its pre-turn statistical description.

These effects may be captured to a certain extent through a model in which the sinusoidal trajectories in the three regimes are required to smoothly connect. By "smoothly," we mean

- No sudden jumps in vessel position
- No sudden jumps in the vessel's velocity direction (over the ground)

The second condition does *not* imply that the slope of the trackline itself must be continuous over the three regimes of the turn. Figure 5.1-1 illustrates this situation as

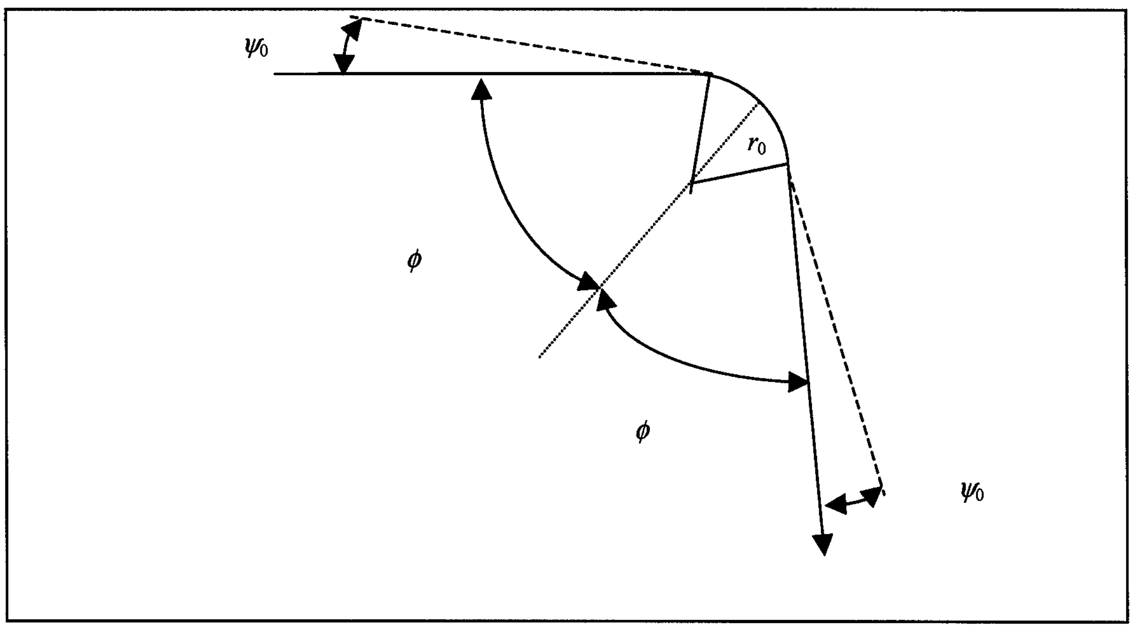


Figure 5.1-1. Trackline configuration at a turn.

a turn executed from left to right with total turn angle equal to $\pi - 2\phi$. The two dashed lines are tangent to the circular arc trackline at the two ends of the arc. The dashed line meeting the two solid lines in the middle of the figure defines the radius of curvature, $r_0$, for the circular arc trackline. The opening angle for this arc can be shown to be $\theta - 2\psi_0$

and thus the distance in the turn is given as $r_0(\theta - 2\psi_0)$. Thus, the trackline jumps by an angle $\psi_0$ at the beginning and end of the circular arc trackline. Note that these results lead to a constraint on $\psi_0$, i.e., $\psi_0 < \theta/2$.

In the pre-turn regime, the incident model describes, as noted above, the vessel trajectory as a sinusoid with random amplitude whose distribution is given by the King's Point data and a random walk phase. Moreover, this sinusoid is offset from the channel centerline by the error introduced by the guiding navigation system. This error is assumed to have zero mean and a standard deviation characteristic of the navigation system. In this regime, the wave number, defined by $k = \omega / v$, is specified by the radian frequency $\omega$, obtained from the King's Point data, and the operating velocity, $v$, chosen by the NAAT user.

In the post-turn regime, the amplitude and wave number are assumed to be the same as that in the pre-turn regime. The phase of the sinusoid is determined from the boundary conditions as discussed below. Those readers not concerned with the details of the turn model may skip to Section 5.2 at this point.

The boundary conditions result from enforcing continuity of the vessel trajectory and its slope at the interface between the first and second regimes and the interface between the second and third regimes. Application of these boundary conditions result in four equations that must be solved for the following four quantities:

- Sinusoid amplitude in the second regime (turn segment)
- Phase in the second regime
- Wave number in the second regime
- Phase in the third regime

Reduction of the equation set is complex and leads to transcendental equations that must be numerically solved. The solution process results in discrete values (eigenvalues) for

the wave number in the turn segment. The appropriate wave number value in the turn segment, $k_t$, is selected using the following procedure:

1 The NAAT operator picks the vessel speed, $v_t$, in the turn segment (default is the regime 1 velocity divided by 5)

2 The quantity $\omega / v_t$ is computed, where $\omega$ is the radian frequency of the vessel from the first regime (straight segment)

3 The discrete $k_t$ spectrum is truncated by requiring $k_t > \omega / v_t$ ; the minimum value of the allowed $k_t$ is then selected

4 All other unknown quantities listed above may be expressed in terms of this selected $k_t$ value; the quantity of principal interest is the trajectory amplitude in the turn segment.

The rationale for Step (3) in the above procedure is that the selected wave number should be reasonably close to the radian frequency used throughout most of the transit. The inequality, $k_t > \omega / v_t$ , implies that the vessel will actually execute a slightly different sinusoidal frequency, $\omega' = k_t v_t$ , where $\omega' > \omega$. This is consistent with expected practice at turns where a higher degree of control implies a higher frequency for the vessel trajectory.

The plot shown in Figure 5.1-2 illustrates the procedure. This plot shows the allowed wave numbers in the turn segment for various turn angles. The scenario for this plot consists of the following parameters:

- a 2 km distance in the turn
- turn radius of curvature of 10 km
- a trajectory amplitude of 4.5 m
- a 6-minute trajectory period in regime 1
- vessel speed of 10 kts in regime 1
- a trajectory phase angle of 45° at the interface of regimes 1 and 2

The plot indicates that there are fewer allowed wave numbers at greater turn angles.

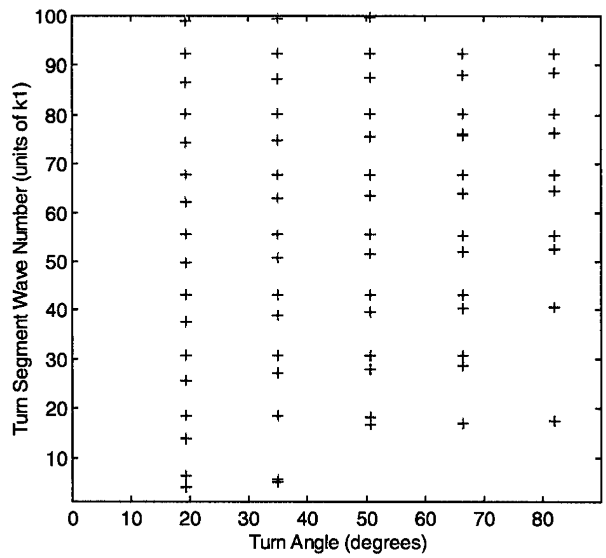


Figure 5.1-2. Discrete turn segment wave number spectrum as a function of turn angle.

As explained in the procedure above, a wave number is selected by first truncating the spectrum through the elimination of all wave numbers less than $\omega / v_t$. In this scenario we take $v_t = v/5$, which corresponds to $k_t = 5k_1$, where $k_1$ is the wave number in regimes 1 and 3. This procedure is illustrated in Figure 5.1-3 which is the same as Figure 5.1.2, except that the wave number spectrum has been truncated to include only $k_t > 5k_1$. For each turn angle shown in the figure, the selected wave number is the minimum above the line $k_t = 5k_1$ corresponding to $v_t = v/5$.

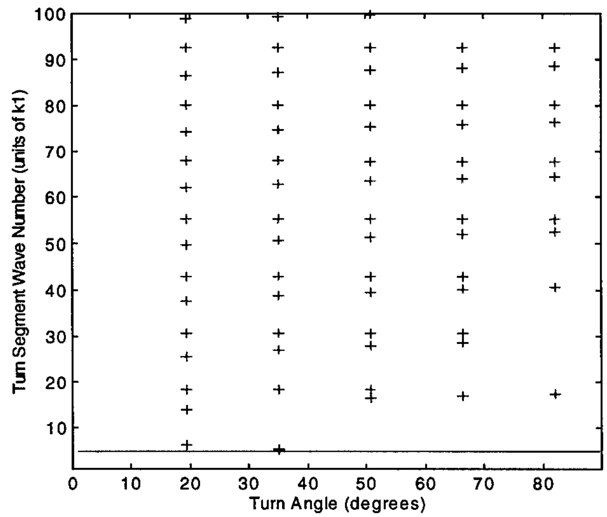


Figure 5.1-3. Turn segment wave number spectrum truncated to permit selection of closest eigenvalue.

## 5.2 Sample Results

The amplitude of the trajectory in the turn segment (regime 2) depends on the selected wave number eigenvalue as well as the other parameters in the scenario. Figure 5.2-1 shows a plot of the turn segment amplitude as a function of turn angle. Here the amplitude has been averaged over all possible trajectory phase angles occurring at the initiation of the turn segment. In this scenario, the distance in the turn is a constant 2 km and the turn radius of curvature is 10 km. Note that the turn segment amplitude is in units of $A_1$, the trajectory amplitude in regimes 1 and 3 (about 4.5 m). In general, the plot shows the amplitude increasing with turn angle, as expected. However, there is a dip between 40° and 50° due to wave number eigenvalue shifts.

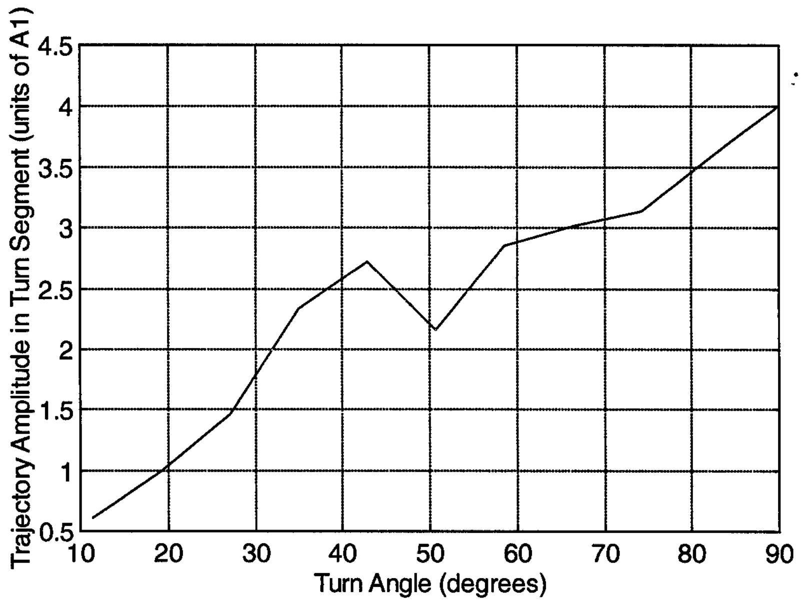


Figure 5.2-1. Trajectory amplitude in the turn segment as a function of turn angle.

The turn amplitude results can be used in calculating the incident rate (Morris and McGaffigan, 1999a) if we assume that the computed amplitudes (such as those shown in Fig.5.2-1) represent standard deviations of the randomly varying amplitude. The free half-channel in the turn segment is computed using the following procedure:

- take the average of the two interface boundary widths (see Figure 4.2-3)
- subtract the width of the vessel, accounting for any crab angle (see Section 4.2.4)
- divide by two

This procedure is used for the following reasons: (1) the boundaries of the real channel are not well-defined in the turn segment and (2) it yields a conservative bound on the incident rate consistent with the conservative approach used in this model.

Figure 5.2-2 shows the results of incident rate calculation as a function of turn angle for two hypothetical scenarios:

- Use of DGPS ($\sigma_N = 2.9$ m) on a large vessel (100' beam) in a narrow channel such as the St. Mary's River/Rock Cut where the free half-channel width is 100 feet
- Use of Loran-C (on the same vessel) with three stations in Tampa Bay area (least accurate configuration geometry; $\sigma_N$ = 13.55 m) where the free half-channel width is 200 feet.

Of course, the designated navigation areas, St. Mary's River and Tampa Bay, do not necessarily have turns at some or any of the turn angles/free half-channel widths included

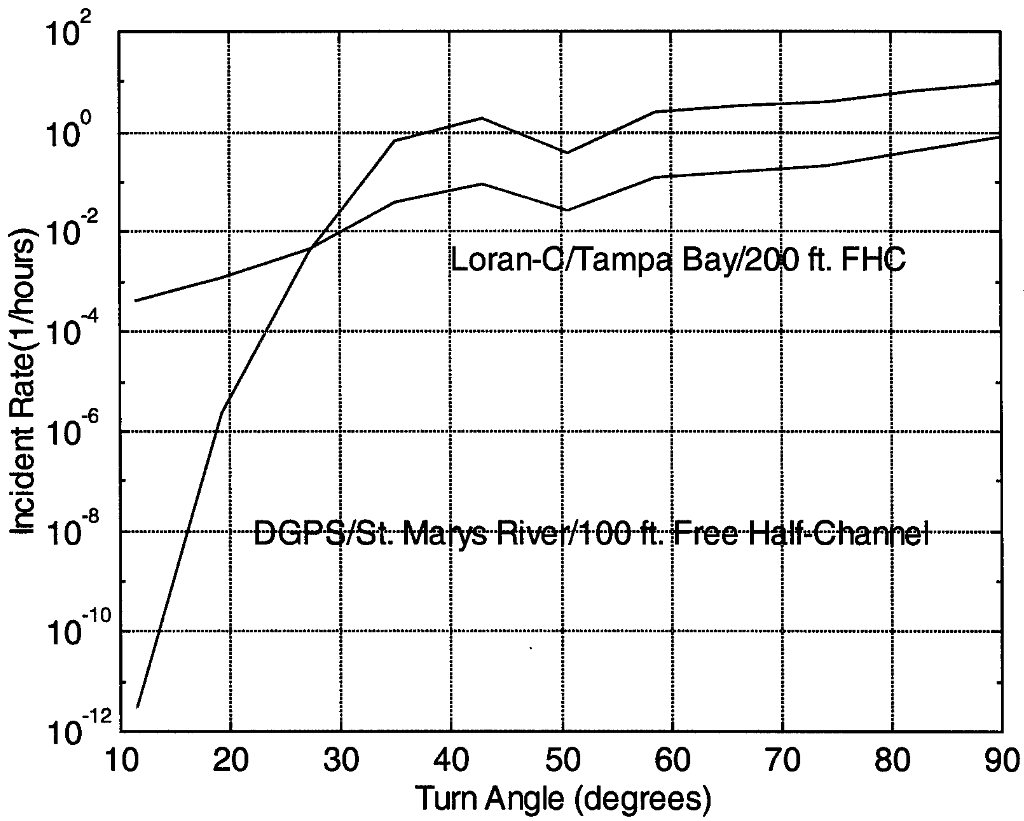


Figure 5.2-2. Incident rate as a function of turn angle for two hypothetical scenarios.

in the plot of Figure 5.2-2. The figure merely indicates the degree of sensitivity of incident rate to turn angle

The semi-logarithmic plot in Figure 5.2-2 shows that, although the incident rate for the DGPS/St. Mary's River scenario is some eight orders of magnitude less than that for the Loran-C/Tampa Bay case for low turn angles, when the turn angle reaches somewhat under 30°, the incident rate for the DGPS/St. Mary's River scenario is larger. For turn angles from 35° - 90°, the incident rate for the DGPS/St. Mary's River scenario exceeds that of the Loran-C/Tampa Bay scenario by a roughly constant factor of 10.

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# 6. Summary, Conclusions, and Recommendations

## 6.1 Summary of Task 1 – Visual Aid Navigation Incident Model Development

In this report we have described the principal components of a methodology for computing the incident probability for vessels navigating a two-dimensional channel using visual aids. The methodology is also compatible with the overall Markov model so that visual aids can be treated as a "navigation system," on equal footing with other navigation systems.

By approximating the channel segments as symmetric trapezoids, the technique captures the essential features of real channel geometry. The report describes a visible aid coverage algorithm that accounts for both atmospheric visibility and effective aid range. This algorithm is applied at the beginning of each segment although it tests for aid visibility throughout the entire forward portion of the channel. An effective free half-channel calculation uses the vessel's size parameters (beam and length) as well as current direction and magnitude as input.

An empirical model for computing the incident rate when using visual aids is developed based on the statistical analysis of channel complexity factors in the *Port Needs Study* casualty database. Though not based on specific mechanisms relating aid positioning and visibility to navigation accuracy, the method is directly tied to the TLS and includes an *ad hoc* functional dependence of incident rate on the <u>number</u> of aids visible at the beginning of a channel segment. For the situation in which no aids are visible (due either to low visibility or failure of one or more aids), a blind segment model for calculating incident probability is formulated. Based on an assumed dead reckoning mode of navigation, this method yields high incident rates for long, narrow channel segments.

## 6.2 Summary of Task 2 – Dynamic Markov Chain Generation for NAAT

This report explains several of the key developments necessary for the application of the Markov model for navigation system-related incident rate and failures to the user-oriented Navigation Aid Analysis Tool. In particular, this task addresses the need to dynamically configure the Markov chain so as to compute the probability of being in the incident state for an arbitrary selection of vessel/navigation system/navigation area. This task also addressed the augmentation of the incident model to include certain two-dimensional effects, specifically turns.

The dynamic Markov chain generation is structured in terms of four principal steps:

1. Define on-board equipment (user input)
2. Generate states to be included in the Markov Chain
3. Determine navigation operation mode for each mode
4. Determine connections and insert transition rates

The state generation and specification of the navigation operation mode is implemented by creating the appropriate binary word in which bit position represents navigation system priority. Although this technique generalizes the procedure, certain disallowed states and exceptional conditions (due to interdependencies between navigation systems) must be recognized and appropriately treated. A particular challenge has been to adapt INS/IMU to the Markov chain. The technique accounts for a unique asymmetry in the INS/IMU failure and recovery links.

Vessel and navigation area catalogs are established to facilitate the operation and use of NAAT. Although new vessels and navigation areas can always be created, it is expected that the NAAT operator will frequently wish to explore certain situations using previously studied vessels and navigation areas. Vessel catalogs are rather simple,

requiring only three parameters, in addition to the vessel type. Navigation area catalogs, however, include a more extensive set of data that can be categorized as

- Turn point data
- Channel segmentation data
- Visual aid data

The turn point data refers to those quantities necessary to compute the incident rate at turns. The channel segmentation data provides the additional information necessary to specify the channel geometry and other characteristics. Visual aid data includes the position, type, visible range, and reliability of the visual aids assigned to the navigation area of interest.

As in the case of vessel catalogs, the NAAT operator can always create a navigation area. However, a segmentation algorithm was developed to reduce the workload of the NAAT operator in building a scenario. In most cases, it is expected that the easiest procedure for the NAAT operator is the input of basic information, e.g., coordinates for the initial and final transit points as well as the turn points, followed by the segmentation algorithm, which establishes a default channel segmentation. The NAAT operator can then edit the segmentation output "by hand" or input values from a database.

The incident model developed in the previous effort with NAVCEN (Morris, 1999a) basically addressed the navigation and vessel control errors in a single dimension — cross-track — applicable to vessels operating in straight channel segments. In this task, the model was extended to include the transitions between straight channel segments, i.e., turns.

First, a turn segment is defined as the interface between the last segment of a straight channel section and the first segment of the next straight channel section (at a different angular orientation). The turn angle is the same as the opening angle between

the two interface boundaries of the turn segment. In the straight sections, a sinusoidal trajectory results from attempts to steer the vessel to the desired trackline (assumed to be the channel centerline). In the turn segment, the trackline is assumed to be the arc of a circle with user-selectable length and fixed radius of curvature. The model is based on the assumed continuity of the trajectory and the slope of its tangent at the turn segment boundary interfaces.

The NAAT operator may also pick the vessel speed in the turn segment (default is $0.2 \times$ speed of the vessel in the preceding and following segments). From this value, the model selects the turn segment trajectory with allowed sinusoidal frequency closest to, but greater than, the frequency in the straight segments. This is expected to capture, to some degree, the maneuvers in the turn region where a vessel slows and higher-frequency control is needed to properly execute the turn. The quantity of interest computed by the model is the trajectory cross-track amplitude, which is generally larger than the straight channel section amplitude. The amplitude is also found to generally increase with turn angle.

If the computed turn segment amplitude values are taken to represent trajectory amplitude standard deviations from a statistical process, the incident rate is readily calculated in the turn segment. The free half-channel is conservatively taken to be the average of the turn segment interface boundary widths. The incident rate is found to generally increase sharply with increasing turn angle.

## 6.3 Discussion

Navigation by means of visual aids is easy to describe, but quantifying the precision afforded by this technique is extremely difficult. Part of the problem stems from the difficulty in modeling the pilot's eye/brain processing of the visual aid images and the subsequent translation to motor neural activity. The processing depends on a very large number of factors, including pilot experience and skill level. Nevertheless, a means has

been found to capture the basic elements that affect navigation accuracy and quantify these elements by establishing measures of their effects.

One advantage of the incident analysis carried out in this report is that we are not concerned with the entire distribution of navigation accuracy — only the tails of the error distribution in which vessel incidents, or groundings, occur. The statistical technique described in this report for the *empirical visual aid incident rate model* ties in naturally to the data used as the basis for computing the target level of safety (TLS). Its predictive performance is predicated on two basic assumptions:

- Most of the historical casualty data addresses those operations conducted with the use of visual navigation
- The principal statistical parameters derived from the historical casualty data apply equally well to future vessel operations.

The latter assumption may apply well to future visual navigation operations but its validity for future radionavigation operations, especially DGPS, is uncertain. The uncertainty arises because DGPS is an *enabling* technology, i.e., its high precision means that low-visibility operations formerly considered too risky with less accurate radio aids, can now be undertaken with roughly the same margin of safety. At this point, it is too early to say whether the increase in attempted operations under riskier conditions as enabled by the new technology will result in fewer or more incidents.

At the other end of the spectrum, an incident model has been constructed to apply to scenarios in which *no* aids (radio or visual) are available. This model is a "first principles" type (i.e., no dependence on statistical parameters derived from historical incident data) that effectively emulates a dead reckoning mode. The only inputs to this *blind segment incident rate model* that are "internal," i.e., dependent upon operator judgment or skill, are the two standard deviations (from the channel centerline) for angular deviation and cross-track displacement.

Development of the dynamical Markov state space model for incident rate calculation with operator input of navigation systems and use precedence, as well as

navigation area and vessel type, is complicated by the "exceptional" behavior of certain systems. This exceptional behavior results from interdependencies between navigation subsystems, e.g., DGPS and GPS, and, in the case of INS, non-reciprocal transitions between certain system states. In addition to specifying the navigation systems/aids to be used by the vessel in transiting the navigation area, the NAAT input scenario must indicate the *precedence* of the systems, i.e., the use hierarchy (primary, secondary, etc.). The precedence hierarchy dictates that, at any given time, the only system being used for vessel navigation is the system with the highest precedence of those that are functioning normally. This is a rather conservative assumption, since it implies that the vessel is controlled by reference to a single navigation system as long as that system has not failed. This conservative assumption can be partially offset by emulating the condition that some or all backup systems are continuously calibrated by the next higher-priority functioning navigation system in the hierarchy. Thus, for example, to emulate the situation in which the primary DGPS system continuously calibrates the backup Loran-C system, one of the DGPS service reliability parameters (mean time to restore) may be appropriately shortened (Morris, 1999a).

From the macroscopic view, navigation in many maritime navigation areas is a one-dimensional problem. This is especially true for operations with large vessels (200 m) in the navigationally challenging narrow channels having widths comparable to vessel lengths. In those areas where the channel significantly changes direction, i.e., turns, the two-dimensional aspect of navigation is inescapable and must be explicitly included in the analysis. Actual turn maneuvers involving specific vessels are quite complex (Smith, 1992) and not easily incorporated into the more general incident models developed here as the basis of NAAT.

The analysis described in this report develops incident models for turns for both visual navigation and radionavigation. For visual navigation, the empirical model contains a "complexity factor" term for turns that effectively increases the incident rate in proportion to the turn angle. The incident model for turns using radionavigation systems is considerably more complex since it extends the combined piloting error and navigation

error models developed earlier (Morris, 1999a). In this picture, the vessel executes a sinusoidal trajectory (few-minute period) about a slowly changing cross-track bias error. The amplitude of the sinusoidal trajectory is taken to be a parameter from a statistical distribution of observed amplitude data. In the turn, the amplitude ratio (referenced to the straight-segment amplitude) is based on the assumption of continuity in both the trajectory position and velocity of the vessel. This assumption gives rise to larger amplitudes in turns (compared to straight segments) and thus increased incident rates.

## 6.4 Recommendations

In its current form, NAAT only computes probabilistic parameters for incidents arising from vessel collisions with the edge of the channel (groundings). A large class of incidents stems from collisions between vessels operating in the same channel (overtaking or opposing). Extending the current model to include vessel-vessel collisions would provide a more realistic assessment of the total incident rate.

Navigation using marine radar is currently treated entirely separate from visual navigation. However, it is known that pilots use the two methods synergistically in actual practice. This dependence should be captured in a revised model basis for NAAT.

The next step in applying NAAT to the Aid Mix problem is to perform an independent verification and validation (IV&V). An IV&V will ensure that the NAAT implementation is as described and that NAAT provides valid information when used.

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# 7. References


Creamer, P., Cho, D., Morris, P., Pisano, J., (1997) Differential GPS Mission Needs Analysis: Harbor Entry and Approach, TASC TIM 08605-1.

Kite-Powell, H., Patrikalakis, N., Jin, D., Abrams, S., Jebsen, J., Papakonstantinou, V., Lin, S., (1998) Formulation of a Model for Ship Transit Risk: Final Project Report, MIT Sea Grant College Program Report No. 98-7.

Maio, D., Ricci, R., Rossetti, M., Schwenk, J., and Liu, T., (1991) Port Needs Study (Vessel Traffic Services Benefits) Report, Volumes I – II, DOT-CG-N-01-91-1.2.

Morris, P. and McGaffigan, D., (1999a) Differential GPS Harbor Entrance and Approach Requirements Analysis, Volumes I, II, TIM 09262-3.

Morris, P. and McGaffigan, D., (1999b) Visual Navigation Analysis.

Morris, P. and McGaffigan, D., (1999c) DGPS Mission Needs Analysis Adaptation.

Smith, M., (1992) Waterway Design Manual, Report No. CG-D-18-92, USCG Research and Development Center.